THE FUTURE OF U.S. FUSION ENERGY RESEARCH

HEARING

BEFORE THE

SUBCOMMITTEE ON ENERGY

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

HOUSE OF REPRESENTATIVES

ONE HUNDRED FIFTEENTH CONGRESS

SECOND SESSION

MARCH 6, 2018

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THE FUTURE OF U.S. FUSION ENERGY RESEARCH

TUESDAY, MARCH 6, 2018

HOUSE OF REPRESENTATIVES,
SUBCOMMITTEE ON ENERGY
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY,
Washington, D.C.

The Subcommittee met, pursuant to call, at 10:08 a.m., in Room 2318 of the Rayburn House Office Building, Hon. Randy Weber [Chairman of the Subcommittee] presiding.

LAMAR S. SMITH, Texas
CHAIRMAN

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RANKING MEMBER

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House of Representatives
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Subcommittee on Energy

The Future of U.S. Fusion Energy Research

Tuesday, March 6, 2018
10:00 a.m.
2318 Rayburn House Office Building

Witnesses

Dr. Bernard Bigot, Director-General, ITER Organization

Dr. James W. Van Dam, Acting Associate Director, Fusion Energy Sciences, Office of Science, U.S. Department of Energy

Dr. Mickey Wade, Director of Advanced Fusion Systems, Magnetic Fusion Energy Division, General Atomics

Dr. Mark Herrmann, Director, National Ignition Facility, Lawrence Livermore National Laboratory

U.S. HOUSE OF REPRESENTATIVES
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

HEARING CHARTER

Tuesday, March 6, 2018

TO: Members, Subcommittee on Energy

FROM: Majority Staff, Committee on Science, Space, and Technology

SUBJECT: Subcommittee hearing: "The Future of U.S. Fusion Energy Research"

The Subcommittee on Energy will hold a hearing titled *The Future of U.S. Fusion Energy Research* on Tuesday, March 6, 2018, at 10:00 a.m. in Room 2318 of the Rayburn House Office Building.

Hearing Purpose:

The purpose of the hearing is to explore the status of basic research on nuclear fusion energy including U.S. international partnerships, domestic research programs, and private sector innovation. This hearing will specifically examine U.S. participation in the International Thermonuclear Experimental Reactor (ITER) project in France, an international initiative to build the world's largest tokamak reactor, and address the current status of ITER engineering, construction, and management.

Witness List

- **Dr. Bernard Bigot**, Director-General, ITER Organization
- **Dr. James W. Van Dam**, Acting Associate Director, Fusion Energy Sciences, Office of Science, DOE
- **Dr. Mickey Wade**, Director of Advanced Fusion Systems, Magnetic Fusion Energy Division, General Atomics
- **Dr. Mark Herrmann**, Director, National Ignition Facility, Lawrence Livermore National Laboratory

Staff Contact

For questions related to the hearing, please contact Hillary O'Brien of the Majority Staff at 202-226-8984.

Chairman WEBER. The Subcommittee on Energy will come to order. Without objection, the Chair is authorized to declare recesses of the Subcommittee at any time.

Welcome to today's hearing entitled "The Future of U.S. Fusion Energy Research." I recognize myself for five minutes for an opening statement.

Today, we will hear from a panel of experts on the status of U.S. fusion energy research and discuss what we can do as a nation to advance this critical area of discovery science. The goal of fusion research is to create a star here on Earth and control it to the point that we can convert its immense heat into electricity. Easy, right? In the center of stars like our sun, extreme temperatures, pressures, and gravitational conditions create a unique natural environment for fusion to occur. On Earth, scientists push the boundaries of experimental physics in a number of ways to duplicate these reactions, with the hopes of eventually generating fusion energy as power we can use in everyday activities.

The potential benefits to society from a fusion reactor are beyond calculation: the fuel is abundant and widely accessible, the carbon footprint is zero, and the radioactive waste concerns are minimal. Despite these incentives, Fusion Energy Science remains one the most challenging areas of experimental physics today.

Generally speaking—and don't worry, I'll leave the detailed explanation to our panel of expert witnesses—Fusion Energy Science is the applied study of a plasma, or ionized gas, and is dependent on three main conditions: plasma temperature, density, and confinement time. During this hearing, you'll hear terms like "inertial confinement" and "tokamak." These are different techniques and devices used by scientists to control these three quantities in their experiments as they work to successfully generate fusion energy.

The Department of Energy (DOE) supports fusion research primarily through its Fusion Energy Sciences (FES) program within the Office of Science. Domestically, it funds robust research through its national labs and partnerships with industry.

At Lawrence Livermore National Lab, the National Ignition Facility, or NIF, pursues ignition in the lab by using a high-energy laser to induce inertial fusion and provide critical science for DOE's nuclear stockpile stewardship mission.

The DIII–D National Fusion Facility, a DOE user facility managed by General Atomics, is the largest magnetic fusion facility in the United States. This program seeks to provide solutions to operational issues that are critical to the success of tokamak-style fusion reactors like the International Thermonuclear Experimental Reactor (ITER) project. Considered the leading research innovation—initiative in fusion science, the ITER project is a major international collaboration to design, to build, and to operate a first-of-a-kind research facility to achieve and maintain a successful fusion reaction in the lab.

Though located in France, ITER is also a U.S. research project. Over 80 percent of total U.S. awards and obligations to ITER are carried out in the United States. As of December 2017, the U.S. ITER Organization has awarded more than $975 million in research and engineering funding to approximately 600 U.S. laboratories, companies, and universities.

The DOE's fiscal year 2019 budget request for ITER is $75 million, well below the required commitment level to keep the project on track. If enacted, this may result in damaging delays to the ITER project and sends the wrong message to the international fusion community about America's commitment to its international agreements and our leadership in science.

When determining the next steps for the domestic U.S. fusion energy program, we must consider the importance of access to the ITER reactor for American researchers and America's standing and credibility as a global scientific collaborator. If the United States is going to lead the world in cutting-edge science—and we hope it does—we cannot take our commitments to our international partners lightly.

I want to thank our accomplished panel of witnesses for their testimonies today, and I look forward to a productive discussion about this exciting area of research.

[The prepared statement of Chairman Weber follows:]

COMMITTEE ON
SCIENCE, SPACE, & TECHNOLOGY
Lamar Smith, Chairman

For Immediate Release
March 6, 2018

Media Contacts: Thea McDonald, Brandon VerVelde
(202) 225-6371

Statement by Chairman Randy Weber (R-Texas)

The Future of U.S. Fusion Energy Research

Chairman Weber: Good morning and welcome to today's Energy Subcommittee hearing. Today, we will hear from a panel of experts on the status of U.S. fusion energy research and discuss what we can do as a nation to advance this critical area of discovery science.

The goal of fusion research is to create a star here on earth and control it to the point that we can convert its immense heat into electricity. Easy, right? In the center of stars like our sun, extreme temperatures, pressures and gravitational conditions create a unique natural environment for fusion to occur.

On earth, scientists push the boundaries of experimental physics in a number of ways to duplicate these reactions, with the hopes of eventually generating fusion energy as power we can use in everyday activities.

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If enacted, this may result in damaging delays to the ITER project, and sends the wrong message to the international fusion community about America's commitment to its international agreements, and our leadership in science.

When determining the next steps for the domestic U.S. fusion energy program, we must consider the importance of access to the ITER reactor for American researchers and America's standing and credibility as a global scientific collaborator. If the U.S. is going to lead the world in cutting edge science, we cannot take our commitments to our international partners lightly.

I want to thank our accomplished panel of witnesses for their testimony today, and I look forward to a productive discussion about this exciting area of research.

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Chairman WEBER. I now recognize the Ranking Member, the gentlewoman from California, for her opening statement.

Ms. LOFGREN. Thank you very much. Just a note that the actual Ranking Member is in Texas today. It's the election day in Texas. So I'm happy to be able to fill in, and I thank you, Mr. Chairman, for holding this hearing and for the wonderful witnesses that we have before us.

As the Chairman has said, fusion is the process that powers the sun and stars, so we know it works, but, as all the witnesses here will be able to discuss in far more detail than me, controlling and harnessing a fusion plasma here on Earth is one of the most difficult challenges that our nation and indeed the world's top scientists and engineers are working to address.

That said, if we're successful, then fusion has the potential to provide abundant, reliable, emission-free, and practically limitless energy to meet a large portion of our electricity needs in the foreseeable future. Given the huge potential benefits of developing a viable approach to fusion energy, I believe that this is an area we should be strongly investing in.

Unfortunately, that's not what we're seeing in the Department of Energy's recent budget request for fiscal year 2019 which would cut the Office of Science's fusion research program by about 11 percent and would also entirely eliminate ARPA–E, which is currently supporting a portfolio of innovative fusion projects that could point the way to producing fusion energy quickly and at a lower cost.

Lastly, as I'm sure will learn more about from Dr. Herrmann, the budget for the DOE NNSA inertial confinement fusion program, including support for the National Ignition Facility at Lawrence Livermore National lab, would be slashed by 20 percent. Now, the focus of this program is actually of course not on energy but on ensuring the reliability of our nation's nuclear weapons stockpile. Yet, because there is currently no ongoing federally supported program to develop inertial fusion concepts specifically for energy applications, this weapons-relevant work is currently the only way that many of these concepts are able to advance. So these major cuts could be, you know, very bad for both our national security and our energy future.

I'd like to note, as the Chairman has, that support for the U.S. contribution to ITER would receive an increase in this request but that the actual level of $75 million is below our obligation. The most recent official estimates we've received from the Department projected our contribution to be at least $230 million in fiscal year 2018 and $240 million in fiscal year 2019.

And it reminds me, you know, several years ago we were concerned, and expressed concern at this Committee, about whether our international partners would in the end live up to their obligation. They have, and it's now the United States that is at risk of being the deadbeat, so I'm hopeful that we can address that.

These lower investments, you know, do not reflect Dr. Bigot's tenure and the progress that has been made at the site, and we look forward to hearing from him.

I'll just note that the good news is that Fusion Energy Science research has always had bipartisan support here in the Committee and in the Congress. It's always hard to fund what you believe in, but I'm hopeful that we will make progress in that regard again on a bipartisan basis.

And I've had a personal interest in fusion energy since my time first began here in Congress, and I'm hopeful that that long-term interest will finally pay dividends in ignition at one of our leading science facilities.

So with that, Mr. Chairman, I thank you for the hearing and yield back.

[The prepared statement of Ms. Lofgren follows:]

OPENING STATEMENT
Representative Zoe Lofgren (D-CA)

House Committee on Science, Space, and Technology
Subcommittee on Energy
The Future of U.S. Fusion Energy Research
March 6, 2018

Thank you Mr. Chairman for holding this hearing and thank you to the witnesses for being here today. Fusion is the process that powers the sun and the stars. So we know it works! But, as all of the witnesses here will be able to discuss in far more detail than me, it turns out that controlling and harnessing a fusion plasma here on earth is one of the most difficult challenges that our nation's – and indeed the world's – top scientists and engineers are working to address. That said, if they are successful, then fusion has the potential to provide abundant, reliable, emissions-free, and practically limitless energy to meet a large portion of our electricity needs for the foreseeable future.

Given the huge potential benefits of developing a viable approach to fusion energy, I believe that this is an area that we should be strongly investing in. Unfortunately, that's not what we're seeing in the Department of Energy's recent budget request for FY 2019, which would cut the Office of Science's fusion research program by about 11%. It would also entirely eliminate ARPA-E, which is currently supporting a portfolio of innovative fusion projects that could point the way to producing fusion energy far more quickly and at a much lower cost than more conventional approaches.

Lastly, as I'm sure we'll learn more about from Dr. Herrmann, the budget for the DOE National Nuclear Security Administration's Inertial Confinement Fusion program – including support for the National Ignition Facility at Lawrence Livermore National Laboratory – would be slashed by about 20%. Now the focus of this program is actually not on energy, but on ensuring the reliability of our nation's nuclear weapons stockpile. Yet because there is currently no ongoing, federally supported program to develop inertial fusion concepts specifically for energy applications, this weapons-relevant work is currently the only way that many of these concepts are able to advance. So these major cuts could be especially devastating for *both* our national security *and* our clean energy future.

I would also like to note that while support for the U.S. contribution to the ITER international fusion project would receive an increase in this request, the actual level of $75 million is woefully inadequate to maintaining the project's current schedule and minimizing its cost to U.S. taxpayers. Rather, the most recent official estimates we've received from the Department projected our contribution to be at least $230 million in FY18 and $240 million in FY19. Investing substantially less in those years means our "standing army" costs go up because we're paying a lot of the same people to do less work over a longer period of time, all while we aim to maintain our ability to meet our commitments to the project.

These lower investments may have been more justifiable prior to Dr. Bigot's tenure as Director General of ITER began about 3 years ago, when the U.S. was really leading the effort to significantly reform ITER's management after a critical U.S.-led assessment of the project was presented to its governing council. But given the remarkably impressive progress made by Dr. Bigot and his team in getting this project back on track, this budget request now essentially undermines all of our prior efforts and could end up causing the problems that we worked so hard to resolve.

To be fair, support for fusion energy development has really been a bipartisan problem, as there were notable issues with the previous Administration's stewardship of research in this area as well. But the good news is that in this room you will find strong, bipartisan support for your work, and I believe that, working together, we can go a long way toward enabling a brighter future for the fusion research community and for other potentially revolutionary clean energy technologies as well.

Thank you again Mr. Chairman, and I yield back the balance of my time.

Chairman WEBER. I thank the gentlelady.

Let me introduce our witnesses. And, Doctor, I'm coming to you first. Is it—I'm sorry. I now recognize the Ranking Member of the full Committee, Chairman Smith.

Chairman SMITH. Thank you, Mr. Chairman. I'm glad to see you so eager to get on with the hearing, too, and a good hearing it is.

Chairman WEBER. The gentleman's time is expired.

Chairman SMITH. Stop while I'm ahead. Thank you again, Mr. Chairman.

Today, we will hear about the status of fusion energy research and the prospects of future scientific discoveries in fusion energy. The basic purpose of fusion energy is to create the equivalent of the power source of a star here on Earth. By creating and controlling the same nuclear reactions that occur in a star within a fusion reactor, heat from these reactions could be converted into renewable and reliable electricity. It is no surprise that fusion has captured the imagination of scientists and engineers for over half a century.

The Department of Energy has supported basic research in fusion energy since 1951. The DOE Office of Science Fusion Energy Sciences program funds research and science infrastructure at DOE national labs. At the Princeton Plasma Physics Laboratory, scientists conduct fusion research through the National Spherical Torus Experiment Upgrade user facility. NSTX–U is a magnetic confinement fusion device called a spherical tokamak that is currently the most powerful device of its kind in the world.

At Lawrence Livermore National Laboratory, the National Ignition Facility uses the world's largest and highest-energy laser to generate fusion power in the lab with an alternative technique called inertial confinement fusion.

DOE also funds world-class fusion research through its partnerships with industry. At General Atomics, a defense contractor based in California, the DIII–D National Fusion Facility is a tokamak fusion research facility that operates as a DOE user facility through the Office of Science. DIII–D enables scientists from laboratories, private sector organizations, and universities around the world to carry out experiments in cutting-edge fusion research. Someday, the results of this research may provide the scientific foundation for producing power through fusion. This would obviously reduce carbon emissions by a huge amount with major implications for climate change.

The ultimate goal in Fusion Energy Science is to provide a sustainable, renewable, zero-emissions energy source. While we cannot predict when fusion will be a viable part of our energy portfolio, it is clear that this is critical basic science that could benefit future generations.

One major step toward achieving this goal is the ITER project. ITER is a multinational, collaborative effort to build the world's largest tokamak-type fusion reactor in southern France. Sponsored by the European Union, India, Japan, China, Russia, South Korea, and the United States, the ITER project can help answer fundamental challenges in plasma physics and is a key step in achieving commercial fusion energy.

The Director-General of ITER, Dr. Bernard Bigot, will provide an update on the project's advances and challenges for the Committee today. I want to specifically thank him for his leadership of this complex and challenging international research project.

By contributing nine percent of the cost to construct ITER, American scientists will be able to access 100 percent of the discoveries achieved through the project. That's why it is imperative that the U.S. meet its obligations to ITER and fully fund fusion research at the Department.

According to the research community, a minimum of $163 million for in-kind contributions and $50 million in cash contributions in fiscal year 2019 is necessary to maintain the scheduled U.S. contribution to the project. Unfortunately, DOE's fiscal year 2019 budget request for ITER is only $75 million. Reduced annual funding will only delay ITER instruments being built here in the United States and cause construction delays that increase overall project cost.

With countries like India, Japan, China, and Russia partnering through ITER to produce and share cutting-edge fusion research, we cannot afford to lose our seat at the table. In addition, we cannot expect to receive international support for our domestically hosted global research projects like the high-priority Long-Baseline Neutrino Facility at Fermilab if we do not honor our international obligations.

Basic research, like fusion science, provides the underpinnings for groundbreaking new energy technology. Achieving commercial fusion energy technology will require strong U.S. leadership and consistent investment in discovery science. To maintain our competitive advantage as a world leader in science, we must meet our international commitments and continue to support the research that will lead to next-generation energy technologies.

Thank you, Mr. Chairman. I yield back.

[The prepared statement of Chairman Smith follows:]

COMMITTEE ON
SCIENCE, SPACE, & TECHNOLOGY
Lamar Smith, Chairman

For Immediate Release
March 6, 2018

Media Contacts: Thea McDonald, Brandon VerVelde
(202) 225-6371

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The ultimate goal in fusion energy science is to provide a sustainable, renewable, zero emissions energy source. While we cannot predict when fusion will be a viable part of our energy portfolio, it is clear that this is critical basic science that could benefit future generations.

One major step toward achieving this goal is the ITER project. ITER is a multinational, collaborative effort to build the world's largest tokamak-type fusion reactor in southern France. Sponsored by the European Union, India, Japan, China, Russia, South Korea and the United States, the ITER project can help answer fundamental challenges in plasma physics and is a key step to achieving commercial fusion energy.

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To maintain our competitive advantage as a world leader in science, we must meet our international commitments and continue to support the research that will lead to next generation energy technologies.

###

[The prepared statement of Ranking Member Eddie Bernice Johnson:]

OPENING STATEMENT
Ranking Member Eddie Bernice Johnson (D-TX)

House Committee on Science, Space, and Technology
Subcommittee on Energy
"The Future of U.S. Fusion Energy Research"
March 6, 2018

Good morning, and thank you Chairman Weber for holding this hearing. It is clear that a breakthrough in fusion energy research could be a major step in enabling our clean energy future. Fusion has the potential to provide clean, abundant energy to the world, all while producing essentially no greenhouse gas emissions. Though we aren't there yet, the policy decisions and research investments we make now could well enable that key breakthrough to come much sooner.

The largest and most well-known fusion experiment in the world is the ITER project. I had the opportunity to tour ITER in 2015 and was quite impressed with the progress being made under the leadership of Dr. Bigot, and I am very pleased that he is testifying again today. As Director General, Dr. Bigot has brought significant, positive changes to the management of ITER, including a comprehensive and realistic schedule, budget, and plan to get the project back on track. The project is far more transparent, and by all accounts the management team's agility and responsiveness to addressing issues as they arise have improved dramatically under his tenure.

So once again, I thank you for traveling from France to be here with us today, Dr. Bigot, and I look forward to hearing more details on the progress of the project. As you expressed to me previously, ITER can be an important step forward to harness the power of fusion for the benefit of the entire world.

Although ITER tends to get much of the attention when we discuss fusion research, it is certainly not the only fusion-related investment we are making. The funding allocated to ITER in FY 2017 is only about 13% of the DOE Fusion Energy Sciences budget. ITER will solve problems that the fusion research community can build upon, and ensuring its success is crucial. Yet while this experiment has the potential to answer key scientific and engineering questions in fusion energy, the successful operation of ITER alone will not be sufficient to enable the construction of a commercial scale fusion reactor, nor is it the only path forward.

There are many promising fusion energy technologies and concepts worthy of further exploration, and it would be a terrible mistake if we did not find a way to better support these new innovative approaches through federally funded research and development. The Department's Fusion Energy Sciences program is perfectly positioned to create these opportunities, but the funds devoted to it don't seem commensurate with the potential benefits. That is unfortunate.

In this year's budget proposal, the Fusion Energy Sciences program (FES) would receive a $40 million cut, which is a 10.5% decrease from previous year funding. FES is one of only two programs that are slated for cuts of this magnitude in the Office of Science budget. What is most disappointing is that it comes at a time when there is so much more work to do in this field. We should be increasing our investments in fusion research, not slashing them.

During the last Administration, some of the researchers pursuing alternative concepts to achieve fusion energy generation were able to find funding opportunities at DOE – just not from the Office of Science. ARPA-E is currently carrying out a three-year program to explore the potential for one of these concepts to lead to a reactor with far lower costs than more conventional approaches. But again, this Administration fails to recognize this important work and unique opportunity, and instead has proposed to completely eliminate ARPA-E in the last two budget proposals. I am hopeful that informed Congressional leaders will join me in supporting ARPA-E and keep this Administration from shutting it down.

Finally, I would like to welcome Dr. Mark Hermann from the National Ignition Facility (NIF). NIF is a critical component of our nuclear weapons stockpile stewardship program as well as our research efforts to explore the potential of inertial confinement fusion. I am looking forward to your testimony along with that of the other distinguished experts on the panel.

Thank you Mr. Chairman. I yield back.

Chairman WEBER. I thank the gentleman.

Let me now introduce our witnesses. Our first witness today is Dr. Bernard Bigot, Director-General of the ITER Organization. In his distinguished career, Dr. Bigot has held senior positions in research, higher education, and government. Prior to his appointment at ITER, he completed two terms as Chairman and CEO of the French Alternative Energies and Atomic Energy Commission, or CEA. Dr. Bigot was trained at the ENS Saint Cloud and holds an agregation, the highest-level teaching diploma in France, in physical science and a Ph.D. in chemistry. Welcome, Dr. Bigot.

Our next witness is Dr. James W. Van Dam. Am I saying that right?

Dr. VAN DAM. You are.

Chairman WEBER. Okay. Acting Associate Director of Fusion Energy Sciences in the Office of Science at the Department of Energy. Previously, Dr. Van Dam was a Research Scientist, Associate Director, and Director of the Institute for Fusion Studies at the University of Texas in Austin. He was also Director of the U.S. Burning Plasma Organization and Chief Scientist for the U.S. ITER Project Office. Dr. Van Dam completed his graduate study at University of California Berkeley and the Institute of Plasma Physics in Japan. He received his Ph.D. at UCLA and was a postdoc at the Institute for Advanced Study at Princeton. Welcome, Dr. Van Dam.

Our third witness is Dr. Mickey Wade, the Director of Advanced Fusion Systems of the Magnetic Fusion Energy Division of General Atomics. Prior to serving in this role, Dr. Wade was the Director of the DIII–D national fusion program, the largest fusion research program in the United States with roughly 500 researchers from over 90 institutions from around the world. Dr. Wade received his Ph.D. in nuclear engineering from the Georgia Institute of Technology in 1991. He is the author of over 30 first-author papers, a fellow of the American Physical Society, and has served on the editorial boards of Nuclear Fusion and Physics of Plasma. Welcome, Dr. Wade.

I will now recognize the Ranking Member, the gentlelady from California, to introduce our last witness.

Ms. LOFGREN. Well, thank you. I'd like to—although Lawrence Livermore Lab is not in my district, it's in the neighborhood, and so I'm pleased to introduce Dr. Mark Herrmann, who is the Director of the National Ignition Facility at Lawrence.

As the Director of NIF, Dr. Herrmann manages an experimental science facility that serves the National Nuclear Security Administration's Stockpile Stewardship Program, and he pushes the frontier of inertial confinement fusion and discovery science. Before coming to NIF, Dr. Herrmann spent nine years at Sandia National Labs, and prior to that, he was a physicist at Lawrence Livermore National Laboratory. He's a fellow of the American Physical Society. He's won numerous awards for his scientific work and leadership in his field. He received his undergraduate degrees from Washington University at St. Louis and completed his Ph.D. from the Plasma Physics Program at Princeton University. Thank you for being here, Dr. Herrmann. We look forward to hearing from you.

I yield back.

Chairman WEBER. I thank the gentlelady.

I now recognize Dr. Bigot for five minutes to present his testimony. Dr. Bigot?

TESTIMONY OF DR. BERNARD BIGOT, DIRECTOR-GENERAL, ITER ORGANIZATION

Dr. BIGOT. Thank you very much, Chairman Weber and distinguished Members of the Committee, for giving me the opportunity to present you the updated information on the ITER project.

[Slide.]

Dr. BIGOT. This slide shows the current status of the ITER site with the tokamak building and the assembly hall at the center. Today, March 6 is precisely my three years anniversary as ITER Director-General. In March 2015, as you can see, after seven years, progress was quite slow. At that time, the ITER project was in urgent need of reform.

[Slide.]

Dr. BIGOT. I believe we can say with confidence three years later, looking at this new slide, that the questions raised by several ITER members in 2013, 2014 about the capacity to manage this complex international construction project have been properly answered.

As of November 2017, the ITER project has crossed a significant milestone, the completion of 50 percent of the total construction work scope through First Plasma. These terms include design, component manufacturing, building construction, shipping, and delivery assembly and installation. This is no small achievement. Globally, these project performance indicators shows the ITER project is progressing with reliability.

[Slide.]

Dr. BIGOT. On the work site, as you see, the Tokamak Complex, including the tokamak building, the diagnostics building and the tritium building is advancing rapidly. The Assembly Hall is complete and turned over for assembly of the internal equipment. Similar progress is being made on the cryoplant, magnet power conversion building, the cooling water system, and other buildings across the worksite.

Fabrication of the ITER components both onsite and globally worldwide is showing equal momentum. This includes the most complex and major components such as vacuum vessel sectors progressing in Korea and Europe, the cryostat manufactured by India, thermal shield in mass production in Korea, and all superconducting magnets here in the United States to toroidal field magnets in Italy and Japan and poloidal field magnets in Europe, Russia, and China.

Many first-of-a-kind components are requiring an unprecedented combination of size and precision. The further we progress, the more this project illustrates the interdependency of overall performance. This performance also is the best evidence of organizational reforms since 2015: a clear decision-making process, profound integration of the work of the seven ITER members with the ITER Organization, a reliable schedule, and above all strong international project management and project culture.

I am pleased to report continuing validation from external reviews. When I last spoke to this Committee in April 2016, we had received the report of the independent ITER Council Review Group, which was followed one month later by the positive and cautiously optimistic report by the U.S. Secretary of Energy.

[Slide.]

Dr. BIGOT. Since that time, we have had reviews on many aspects of project management, as you see on the slide. Each of these reviews has found that the ITER project is well-managed, while helping us to refine further our methods. We are committed to continuous improvement.

In April 2016, I reported to this Committee that we had set up technical and organizational milestone to demonstrate to the ITER Council that the project is staying on track for success. I am pleased to say that 31 milestones have now been achieved from January 2016 through First Plasma. We remain on track for First Plasma in 2025. Again, this consistent progress cannot be taken for granted. It demands the collective commitment of all ITER members.

This brings me to my final and most important point, to thank the Committee for placing this ITER status update in context because ITER must be understood as an integral element of U.S. fusion research and the next major step toward a burning or self-heating plasma, as underlined by the recent preliminary report of the U.S. National Academies.

ITER is the converging next step in the fusion research roadmap of the U.S. and every ITER member. The shortfall in the contribution of any single member, if it impacts the delivery of components or the capacity of ITER to meet the assembly and installation schedule, will have a cascading strong effect in delays, costs, and the description of fusion research for every other member. It is why I would like to urge the United States to timely comply with their contribution commitment.

[Slide.]

Dr. BIGOT. We are committed at ITER, as you see on this slide, day and night to make this project the model for international collaboration in complex science and technology. We are committed to making ITER a sound investment for the United States, as for all ITER partners. We look forward to a long and fruitful collaboration. Thank you.

[The prepared statement of Dr. Bigot follows:]

Statement of Bernard Bigot
Director-General
ITER International Fusion Energy Organization

Before the
Subcommittee on Energy
Committee on Science, Space and Technology
U.S House of Representatives

The ITER Project: a core element of U.S. fusion research
March 6, 2018

Thank you Chairman Weber, Ranking Member Veasey, and distinguished members of the Committee. I am grateful for this opportunity to present to you the status of progress on the ITER Project. I am particularly pleased to present my ITER report in the context of the overall U.S. fusion research program, because I believe it is appropriate that ITER is understood as an essential and integral element of U.S fusion research.

INTRODUCTION

This precise day marks exactly three years since I accepted the position of Director-General of the ITER Organization. In March 2015, as this Committee well knows, the ITER project was in urgent need of reform. The inherent complexities built into the ITER Agreement were widely viewed as liabilities. Much of the focus was on whether it was possible to effectively manage such a complex international construction project.

By April 2016, when I last addressed this Committee, we had begun to answer this question affirmatively. At that time our organizational reforms had been underway for one year, based on an Action Plan designed to accomplish several specific objectives: effective, efficient technological decision-making; profound integration of the work of the ITER Organization with that of the Domestic Agencies; a comprehensive technological understanding of all aspects of the ITER machine; finalization of design of ITER's critical path components; an updated, challenging, reliable schedule; and above all, a project culture capable of reliably delivering on our commitments while maintaining the highest levels of safety and quality.

The Committee at that time offered its congratulations for our efforts to put the project back on track, and we were very grateful for your expressions of support. One month after that hearing, we were also pleased to receive the report of the U.S. Secretary of Energy, which was cautiously optimistic about the ITER reforms. However, it was also clear at that stage that some scepticism remained as to whether we would be able to fully carry out these reforms, and even more, whether we would be able to sustain our commitments to deliver the project in accordance with the demands of the new ITER schedule and resource estimates.

Now, almost 2 years later, I am pleased to report that we have, in fact, remained on track for success according to the agreed schedule and cost. The ITER project is a maturing enterprise. The organizational reforms are fully in place. According to multiple external reviews that have considered the performance of the ITER Project since 2015, we have established a robust project culture, including implementing strong, effective standards for international project management, systems engineering, and risk management. Most significantly, we have continued to deliver on our construction and manufacturing commitments, in accordance with the expected milestones, working within agreed cost constraints, and we have achieved this performance as a fully integrated ITER team. And further, we are committed to continuous improvement.

Last November, the ITER project reached a significant milestone: the completion of 50 percent of the "total construction work scope through First Plasma." This is no small achievement. It represents the collective contribution and commitment of ITER's seven members. So it was with a sense of pride in that collective accomplishment, as well as a sense of deep gratitude to each member government, that we announced this accomplishment. And we were gratified with the attention we received in the international media: more than 750 news organizations, from printed and online articles to TV and radio channels, reported this milestone in more than 40 countries and 16 languages.

"Total construction work scope," as used in our project performance metrics, is a start-to-finish term. It includes design, component manufacturing, building construction, shipping and delivery, assembly, and installation. Globally, these indicators show that the ITER project is progressing steadily. This has not happened easily. A project of this complexity is full of risks; and our schedule to First Plasma 2025 is set with no 'float' or contingency. Effective risk management is a daily discipline at ITER.

ITER's success so far has demanded extraordinary commitment of the ITER members, high performance project management, and almost perfect integration of our work. Our design has taken advantage of the best expertise of every member's scientific and industrial base. No country, not even the most advanced, could have done this alone. We are all learning from each other, for the world's mutual benefit.

But to be clear: in no way are we spending time at ITER focused on self-congratulations. We have many challenges ahead of us. We are continuing to question ourselves, to welcome external scrutiny, and to learn and improve the way we work on multiple fronts; an expectation of constant improvement is a way of life for this exceedingly complex, first-of-a-kind machine.

Today I would like to describe some aspects of our progress in detail, illustrating the inter-connectivity of our work by providing examples of recent contributions made by the U.S. and each ITER Member. I will also explain the series of external reviews we have undergone in the past few years, which have provided validation for our progress and continued to stimulate improvements. With this narrative, I hope to also demonstrate the importance of ITER as an essential element of the U.S. fusion research program.

THE ITER MISSION: collaboration on the world's first "burning plasma" experiment

To set the stage, let me offer a few words about the ITER mission.

Fusion is the mass-to-energy conversion that occurs in the core of the Sun and all the stars. It is the most common source of energy in the universe, and the most powerful. Every second, our Sun fuses a massive amount of hydrogen into helium and releases a huge amount of energy. It is this fusion reaction that gives the Earth light and warmth.

Scientists and engineers globally have been working on the most effective way to harness fusion for more than six decades of research. The U.S. has been a core player in every stage. This includes the multinational fusion research program hosted in San Diego at the DIII-D tokamak, which Dr. Mickey Wade will describe today in more detail; as well as the National Ignition Facility at Lawrence Livermore National Laboratory, to be presented by Dr. Mark Herrmann. It also includes the Tokamak Fusion Test Reactor (TFTR) and the National Spherical Torus Experiment at Princeton, C-Mod at MIT, the Joint European Torus (JET) in the United Kingdom, KSTAR in Korea, T-10 in Russia, JT-60 in Japan, EAST in China, Tore Supra or WEST in France, the ASDEX Upgrade in Germany, and many others.

From its genesis with President Reagan's invitation in 1985 to consider a large scientific cooperative program, fusion research has been a multinational investment unlike any other science endeavour in history, in terms of its collaborative funding, innovation and brainpower. Globally, fusion scientists agree that the next major step for fusion science and fusion energy is the creation and controlled study of a "burning" or self-heating plasma: a state in which most of the heating of the plasma is coming from the fusion reaction itself.

The Tokamak fusion reactor is the only configuration mature enough to serve as the basis for a burning plasma experiment in the next decades. In order to conduct this experiment with the volume of fusion heating exceeding the surface losses, it must be done at industrial scale—meaning at ITER scale. Thus the ITER Tokamak is the converging next step of all of the magnetic confinement fusion research conducted by all parties, globally, since the late 1950s. The technologies are mature, but there is still much to be gained in terms of industrial expertise and innovation as we push the boundaries of engineering to achieve the necessary combination of scale and precision. And once complete, ITER will enable scientists to observe for the first time, for a duration of several minutes and as often as needed to optimize the process, this state of matter, a "burning plasma" with a fusion self-heating exceeding the external heating power absorbed by the plasma.

The size and timeline of the ITER investment—as well as the past history of fusion research—makes it logical for the world's leading industrial countries to approach this project collaboratively. Seven members, representing 35 countries and more than 80 percent of the annual global GDP and half the world's population, are involved in the construction of this first "star on earth." The ITER Organization serves as owner and coordinator of the ITER facility as well as the nuclear operator. The seven ITER Members are directly providing around 90 percent of the value in the form of procuring and delivering the millions of components that must fit together into a single, functional machine.

This collaboration allows us to continue to pool the best fusion science and engineering minds from around the globe. It lowers the financial and other risks for any one member.[1] And it enables the joint creation and acquisition of industrial capacity and expertise. The spin-off technologies that emerge from ITER's ground-breaking science and technological innovation are applicable to other industries and open significant opportunities for multinational trade.

Two risks also arise from this collaborative approach. First, for an international construction project in which each Member is procuring components that must interface perfectly together,

[1] Unlike many other U.S. multinational engagements, with ITER the U.S. pays only 9.09% of the cost, with 45.46% of the burden borne by Europe. This makes ITER stand out as a highly leveraged U.S. investment.

we cannot allow differences of perspective or method to lead to divergent priorities or silos of operation. Integration is essential. Each of the ITER Members has a track record of success in high-tech enterprises. But each one approaches project management differently. Cultural and national differences can lend complexities to communication, political decision-making, budgetary processes, labour practices, and other aspects. Thus the organizational complexities built into the project structure, together with the complexities of the machine itself, must be intelligently and carefully managed.

Second, it is absolutely vital that each Member approaches the ITER project with a sense of pride, ownership and responsibility. ITER is an international project, but it is also in every way a U.S. project, an experimental platform for U.S. scientists, an essential element of the U.S. fusion research program—just as it is a European project, a Korean project, a Russian project, a project to be owned and operated by, and for the benefit of, every ITER Member.

The 'risk' that arises in this collaboration is that if any ITER Member falls short in meeting its commitments, it jeopardizes not only that country's fusion program, but the fusion program and roadmap of each of its partners as well.

Looking ahead, we know that we will need the continuing commitment and support of every member to maintain the successful performance of the past 3 years. By choosing to build this machine in an integrated way, we have made our success interdependent. A shortfall in the commitment of any member, if it impacts the delivery of that member's components or the capacity of the ITER Organization to meet the machine assembly and installation schedule, will have a cascading effect in delays and costs to all other members.

PROGRESS IN MANUFACTURING AND CONSTRUCTION

For the past 36 months, ITER has maintained a rapid pace in manufacturing and construction, in parallel with enhancement of project management. As I mentioned at the outset, we recently passed the 50 percent mark in the completion of "total construction work scope through First Plasma." Using the same project performance metrics, total average component manufacturing through First Plasma, including building construction, is assessed to be 58 percent complete.

Supported by advances in fusion technology R&D, the production of major ITER components is in full swing. To illustrate both the interdependency of the project and the value being contributed by all Members, I will provide a few selected examples of recent progress made by each Domestic Agency, with a focus where relevant on components that are particularly complex or first-of-kind.

Europe

On-site construction: As part of its 45.46 percent contribution to ITER, Europe is constructing all the buildings of the ITER scientific installation. Today, the European Domestic Agency has completed 42 percent of work on site and signed 74 percent of work contracts.

The Tokamak Complex, incorporating the Tokamak Building, the Diagnostics Building and the Tritium Building, is advancing rapidly (see Figures 1 and 2). The basement levels (B1, B2) as well as the three above-ground levels (L1, L2, L3) of the Tokamak Building and bio-shield are complete. The Diagnostics Building is also nearing completion; whereas the Tritium Building, which is not needed for First Plasma, is currently at the L2 level. Multiple drain tanks have been installed, the first such equipment in the multi-year installation of tokamak and plant systems. The Assembly Building is complete and was turned over for use last year, and installation of the massive Sub-Sector Assembly Tools, manufactured by Korea, is fully underway.

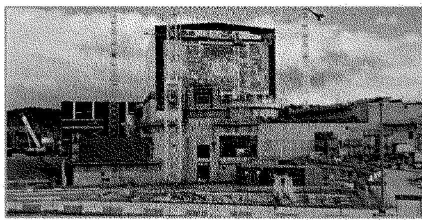


FIG. 1: A view of the Tokamak Complex with the Assembly Hall to the back. The Tokamak Pit is in the centre, the Tritium Building on the left and the Diagnostics Building on the right.

FIG. 2: The bioshield is now finalized. Openings in the wall are for cryostat bellows that will connect the machine to the port cells to give access to systems such as remote handling, heating and diagnostics.

Figures 3 and 4 provide an overview of the change in the worksite from February 2015 to January 2018. As these photos illustrate, overall construction has been progressing rapidly, including the ancillary buildings and structures such as the Radiofrequency Heating Building, the Cryogenics Building, and the Magnetic Power Conversion Buildings, as well as the associated civil works and infrastructure elements.

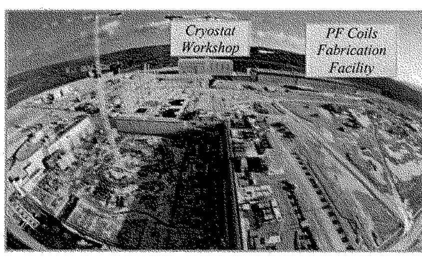


FIG. 3: The ITER worksite in February 2015.

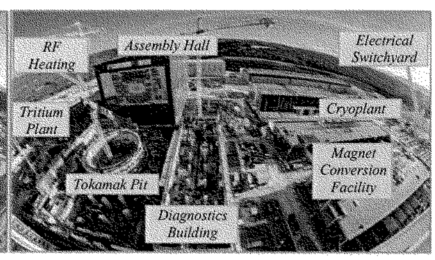


FIG. 4: The ITER worksite in January 2018.

First toroidal field magnet core: Inside the metal torus or donut-shaped vacuum vessel of the ITER Tokamak will be a second, invisible cage created by magnetic fields. These powerful electromagnets will keep the heated plasma in circulation away from the walls. Eighteen of these magnets, called toroidal field magnets, will be integrated around the vacuum vessel. These magnets are being manufactured both in Europe and Japan, using superconductors from six of the ITER Members, including the United States. The first of Europe's toroidal field magnet cores, called a "winding pack" and weighing 110 tons, was completed by the ASG consortium in April 2017 in La Spezia, Italy (see Figure 6).

The magnet core has now been delivered to Italy's SIMIC, the company that will complete cold tests and insert the magnet core into its final case. The completed magnet will then be delivered to the ITER site.

Negative ion beam source: Three systems will be used to heat the hydrogen plasma to 150 million °C, the temperature needed for fusion. The "neutral beam" system will provide more than half the heating for the plasma by injecting two high-energy particle beams of 16.5 megawatts (MW) each into the tokamak vacuum vessel.

The circumference of each particle beam is about 2.5 meters, greatly exceeding the size of previous beams, which had circumference of a dinner plate and a fraction of the power. The size of ITER requires thicker particle beams and faster individual particles in order to penetrate the plasma deeply enough to contribute to its heating. In addition, new high-energy negative ion source technology must be used, instead of the positive ion source technology used in past machines. Years of research have gone into the optimization of these ion sources.

In November 2017, Europe successfully delivered a negative ion source to the SPIDER test bed of the Neutral Beam Test Facility in Padua, Italy. Here the critical components of the system will be tested in advance, before transfer and installation at ITER. Europe, Japan and India are all contributing components. The SPIDER facility will be ready for commissioning later this month.

First cryopump: Six of ITER's cryopumps will maintain an ultra-high vacuum in the 1,400 cubic meter vacuum vessel where fusion takes place. The cryopumps will trap particles on charcoal-coated panels and extract helium ash from the fusion reaction. Each cryopump will weigh 8 tons and stand 3.4 meters tall. Two additional cryopumps will maintain a lighter vacuum in the cryostat, the 8,500 cubic meter chamber that will house the entire tokamak.

After 10 years of intensive R&D in Europe involving 15 high-tech companies—plus four years of fabrication by Germany's Research Instruments and France's Alsyom—the first cryopump was delivered to ITER for testing on 22 August 2017 (see Figure 5). Following mechanical testing at ITER and cryogenic testing at Germany's Karlsruhe Institute of Technology, fabrication of the additional cryopumps will follow.

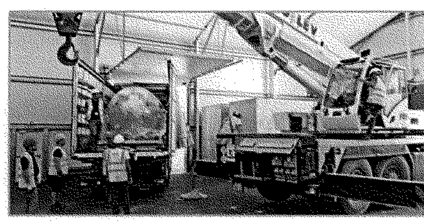


FIG. 5: The pre-production cryopump was delivered in August 2017. More than 15 companies in Europe were involved in its manufacturing.

FIG. 6: The first toroidal field coil winding pack – the 110-ton inner core of ITER's TF Coils – was completed in April 2017.

<u>China</u>

Magnet feeders: ITER's magnet feeders will relay electrical power, cryogenic fluids and instrumentation cables from outside the machine into the superconducting magnets, crossing the warm/cold barrier of the machine. These complex systems are equipped with independent cryostats and thermal shields and packed with a large number of advanced technology components such as the high-temperature superconductor current leads, cryogenic valves, superconducting busbars, and high-voltage instrumentation hardware. They will be among the first components installed.

China is supplying all 31 feeders. The first feeder arrived in France in October 2017.

Correction coils: The correction coils are ITER's smallest superconducting magnets. Weighing no more than 4.5 tons each, they are delicate by ITER standards, much thinner and lighter than the massive toroidal field and poloidal field magnets. Yet their role is vital: to fine-tune the magnetic fields to offset any imperfections in the position and geometry of the main magnets.

China is producing these magnets. Eighteen superconducting correction coils will be distributed around the ITER Tokamak at three levels. Qualification activities have been completed and production is underway on the first coils and cases (see Figure 7).

Electrical conversion components: In addition to the steady state network that will supply electricity to buildings and auxiliary systems, ITER will operate a pulsed power electrical network (PPEN) to deliver power to the magnet coils and the heating and current drive systems during plasma pulses. In mid-2017, China delivered the last of the PPEN voltage transformers; and in October, China delivered four 128-ton converter-transformers for the magnet power conversion system.

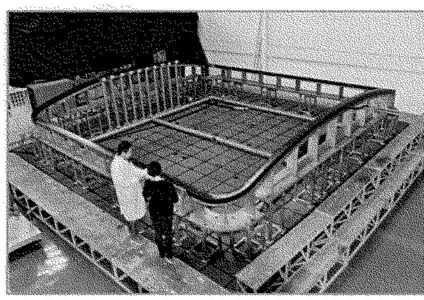


FIG. 7: This full-scale side correction coil prototype was used to qualify winding and impregnation manufacturing steps at ASIPP in Hefei, China.

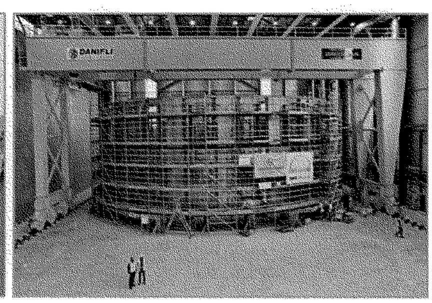


FIG. 8: The ITER scale is apparent in the Cryostat Workshop, where Larsen & Toubro is supervising the assembly and welding of the lower cylinder.

India

Cryostat assembly underway: The 3,800-ton ITER cryostat will be the largest stainless steel vacuum chamber in the world. It will encase the entire vacuum vessel and all the superconducting magnets, ensuring an ultra-cool, protective environment. India is manufacturing the cryostat, but it is far too massive to be shipped as a whole. Steel segments have been precision-fabricated by Larsen & Toubro in India and transported by sea to Marseille. About half of the cryostat pieces have been shipped so far. At the ITER worksite, the Indian Domestic Agency is supervising a team of German welders in the final fabrication of the first two sections—the base and lower cylinder (see Figure 8). Welding operations on the second tier of the lower cylinder should be complete by the end of this month, and the whole assembly (tiers one and two) is expected to be ready for factory acceptance testing in June.

The cryostat base, at 1,250 tons, will be among the heaviest single loads of machine assembly. It will also be the first major component installed.

Cryoline piping: More than five kilometers of "cryoline" piping will be used to deliver cryogenic cooling fluids—liquid helium and liquid nitrogen—to ITER components. These cryolines will travel along an elevated bridge from the cryoplant to the Tokamak Building. From there, the distributed cryoline network will cool the ITER magnets, thermal shield, and cryopumps. The first batch of cryolines was shipped from India to ITER in June 2017.

Japan

Toroidal field coil magnets and cases: Japan has the responsibility for making 9 of ITER's 19 toroidal field coil magnets, as well as all of the cases for these magnets. Japan's first toroidal field winding pack was realized in 2017 by Mitsubishi Heavy Industries Ltd/Mitsubishi Electric Co; a second is underway at Keihin Product Operations/Toshiba Corp.

The steel cases are being made in segments at Mitsubishi Heavy Industries in Futumi, Japan, with some parts contracted to Hyundai Heavy Industries in Ulsan, Korea. They constitute the main structural element of the magnet system—not only encasing the winding packs that make up the core of the toroidal field magnets, but also anchoring the poloidal field coils, central solenoid and correction coils.

In December, the first toroidal field coil case successfully passed all fitting tests. The two sides of this huge component—as tall as a four-storey building and machined from 20-centimeter-thick steel—were matched within gap tolerances of 0.25 mm to 0.75 mm, an accuracy of more than one order of magnitude in relation to conventional high-precision welded structures of comparable size. The case was then shipped to SIMIC in Italy, where the first European winding pack (as mentioned above) has been delivered for insertion.

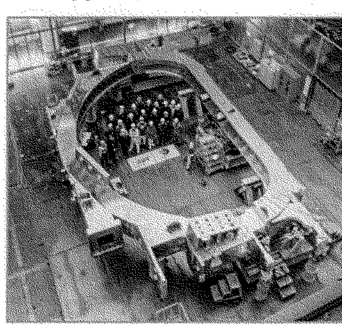


FIG. 9: This toroidal field coil case was manufactured by Mitsubishi Heavy Industries and Hyundai Heavy Industries, in 2 pieces.

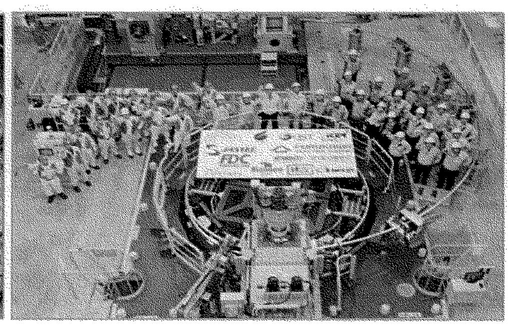


FIG. 10: As of late 2017, Japan has completed the delivery of all niobium-tin superconducting cable to the U.S. for incorporation into the Central Solenoid.

Superconductor for the central solenoid: The central solenoid, the gigantic pillar at the core of the ITER Tokamak, is being built in southern California. But the production of 43 kilometers (745 tons) of special niobium-tin (Nb_3Sn) superconductor that will make up this magnet is the sole responsibility of Japan. In late 2017, Japan completed a major milestone (see Figure 10), shipping the last of this material to the U.S., where it is being wound into the modular coils that make up the central solenoid magnet.

Korea

Vacuum vessel fabrication: The ITER vacuum vessel, a donut-shaped stainless steel chamber heavier than the Eiffel Tower and more than 10 times larger than the next largest tokamak, is being built in nine pieces, like sections of an orange. Each 40° sector is a double walled steel component weighing 500 tons and measuring 12 meters in height and 7 meters in width, with multiple port openings and in-wall shielding contained within its walls in the form of modular blocks. Europe is building five sections, and Korea four. Russia is fabricating the upper ports, and India is making the in-wall shielding.

Korea has recently completed the first segment of vacuum vessel sector #6 on schedule, including non-destructive examination and dimensional measurements (see Figure 11). Sector #1 is nearly half complete, and sector #8 is well underway.

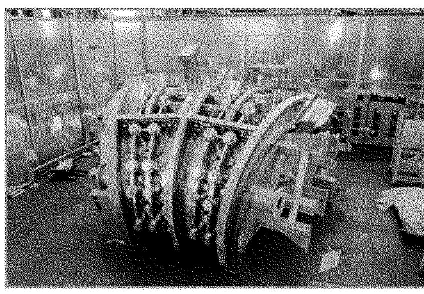


FIG. 11: Korea is nearing completion of the vacuum vessel sector #6. Each sector is made up of four segments. Pictured here is poloidal segment 2.

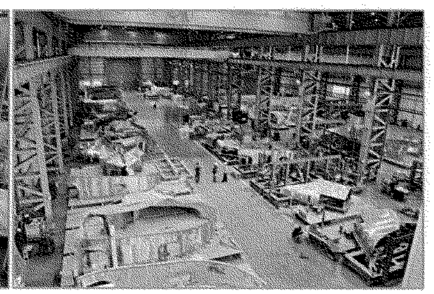


FIG. 12: The 850-ton thermal shield, made up of 600 components that range from a few hundred kilos to approximately 10 tons, is in mass production in Korea.

Giant assembly tools to pre-assemble the vacuum vessel: The tools ITER will use to assemble the vacuum vessel sectors are truly colossal: six stories high with "wings" that spread 20 meters. Each tool weighs 800 tons. Each is strong enough to hold a 440-ton vacuum vessel sector and two 310-ton toroidal field magnets in its arms, bringing them together to make a unit.

Two of these "sector sub-assembly tools" (SSATs) will work side-by-side in the 60-meter-high ITER Assembly Hall. They will pre-assemble the nine sectors of the vacuum vessel with other components before their transfer to the Tokamak Pit, where they will be welded together to form the ITER vacuum chamber.

Korea delivered the first SSAT to ITER in batches in mid-2017. It is currently being erected in the Assembly Hall. A second, identical, tool is under fabrication in Korea.

Thermal shield: Since ITER's superconducting magnets must be cooled to minus 269°C, they must be heavily protected from any heat source. The toroidal field magnets, which surround the vacuum chamber, require a special high-tech thermal shield: stainless steel electroplated in silver. At SFA Engineering Corporation in Changwon, Korea, the fabrication of the ITER thermal shield is now in mass production (see Figure 12).

Russia

Poloidal field coil #1: Six ring-shaped poloidal field coil magnets will encircle the ITER machine to shape the plasma and contribute to its stability by "pinching" it away from the vacuum vessel walls. Poloidal field coil #1 (PF1) is being built at the Srednenevsky Shipbuilding Plant in Saint Petersburg, Russia (see Figure 13). Specialists from the Efremov Institute and other Russian experts are winding niobium-titanium superconductor material into flat "pancakes." The fifth of eight pancakes that will make up the PF1 magnet is now being wound. The final PF1 magnet, which will weigh 300 tons, will be shipped to ITER and installed at the top of the machine.

Poloidal field coil #6 is also well underway in Hefei, China. The remaining four coils, which will be too large to ship, are being manufactured on the ITER site by the European Domestic Agency.

First completed port stub extension for vacuum vessel: As mentioned earlier, the ITER vacuum vessel, where the fusion reaction occurs, will be encased in a second, much larger vessel, the cryostat. Each of the vacuum vessel's 44 openings will have custom-made "extensions" to create the junction to the cryostat. The upper-level ports are being built in Russia. While the extension pieces are small in relation to the vacuum vessel, they are still quite sizable. Port stub extension (PSE) #12, for example, weighs more than 17 tons, covers an opening of 4 meters x 2.5 meters, and is 3.4 meters in length. In November 2017, Russia completed PSE #12 and shipped it to Korea, where it will be welded onto its vacuum vessel sector.

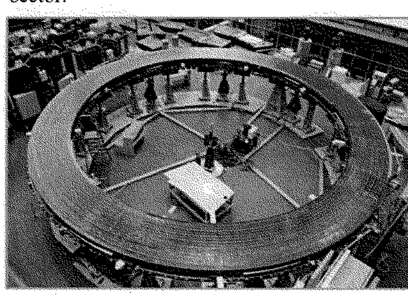


FIG. 13: This double pancake for poloidal field coil #1 in Russia was the first ITER pancake wound following qualification; it has now completed vacuum pressure impregnation to create a rigid assembly.

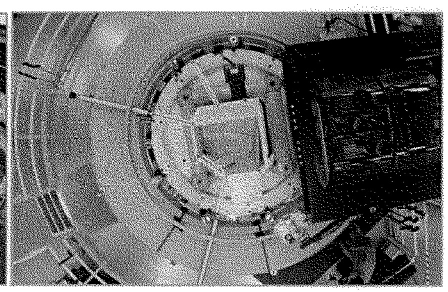


FIG. 14: General Atomics is fabricating the 1000-ton Central Solenoid. Pictured is the first production module. Each module requires approximately 6,000 meters of niobium-tin (Nb_3Sn) conductor.

Power supply and magnet protection system: Russia is responsible for a wide variety of electro-technical components that make up the switching networks, fast discharge units, DC busbars and instrumentation procurement package. Manufacturing is underway now on the busbars and switching network resistors; and the R&D program is concluding for the fast discharge unit components.

__United States__

Central solenoid: In Poway, California, General Atomics is creating the ITER central solenoid, a pillar-like magnet standing 18 meters tall, sometimes called "the beating heart of ITER." The central solenoid is made up of six individual coils, each made from approximately 6,000 meters of niobium-tin (Nb_3Sn) conductor fabricated in Japan (see Figure 14). The central solenoid will be among the most powerful electromagnets ever built, strong enough to lift an aircraft carrier. Its maximum magnetic field will be 13 Tesla, equivalent to 280,000 times the magnetic field of the Earth.

The first of the seven central solenoid production coils is now 80 percent complete, with other coils also in fabrication.

U.S. completes electrical deliveries: The U.S. has completed its contribution to ITER's steady state electrical network (SSEN), which will power the pumps and other non-pulsed auxiliary loads of the ITER facility. The 35th and final shipment of equipment arrived at the ITER site in October 2016 (see Figure 15). The global procurement was managed by Princeton Plasma Physics Laboratory. The U.S. is supplying 75 percent of SSEN components; with Europe supplying the remaining 25 percent.

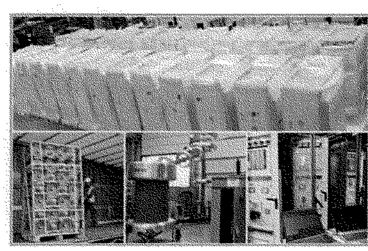


FIG. 15: The U.S. has completed a $34 million, 5-year project to provide 75% of components for the steady-state electrical network at ITER.

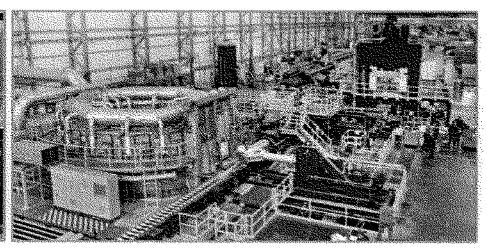


FIG. 16: Fabrication of Tokamak Cooling Water System piping is underway at Schulz Xtruded Products in Robinsville and Hernando, Mississippi. A total of 36 kilometers of nuclear grade stainless steel piping is needed.

U.S. completes Toroidal Field conductor deliveries: The U.S. has completed a $73 million project to complete its contribution to ITER's Toroidal Field system, providing more than 40 tons (4 miles) of superconductor to Europe for its incorporation in toroidal field coils. At the height of fabrication, U.S. vendors Luvata and Oxford Superconducting Technologies were each producing more than five metric tons of superconducting strand per month. Before ITER, worldwide production of this wire was 20 metric tons a year.

Tokamak cooling water system: The Tokamak cooling water system will absorb the heat produced by the ITER fusion reaction. More than 36 kilometers of nuclear-grade stainless steel piping for the system is being fabricated in Robinsville and Hernando, Mississippi (see Figure 16).

In October, the final design review was completed for the entire system—which means that more orders for high-tech equipment need to be placed soon.

Additional U.S. procurements: Several other key components also have to be procured by the U.S.: 4 diagnostic port plugs and 7 instrumentation systems (Core Imaging X-ray Spectrometer, Electron Cyclotron Emission Radiometer, Low Field Side Reflectometer, Motional Stark Effect Polarimeter, Residual Gas Analyzer, Toroidal Interferometer/ Polarimeter, and Upper IR/Visible Cameras); Electron Cyclotron Heating Transmission Lines (approximately 4 km of aluminum waveguide lines—24 lines—capable of transmitting up to 1.5 megawatts per line); Ion Cyclotron Heating Transmission Lines (approximately 1.5 km of coaxial transmission lines—8 lines—capable of transmitting up to 6 megawatts per line); the Pellet Injection System, an injector system capable of delivering deuterium/tritium fuel pellets up to 16 times per second; Vacuum Roughing Pumps, a matrix of pump trains consisting of approximately 400 vacuum pumps; the Vacuum Auxiliary System (vacuum system components including valves, pipe manifolds, auxiliary pumps, etc., and approximately 6 km of vacuum piping); and the Tokamak Exhaust Processing System, an exhaust separation system for hydrogen isotopes and non-hydrogen gases.

Summary of progress: an integrated project

The foregoing is only a sampling of the activity currently underway worldwide, as all ITER Members work to the same integrated schedule, fabricating their components for this intricate and interdependent project. This interdependence will become still more apparent this year, as the final preparations for the Assembly Phase are made and assembly contracts are placed. It will escalate even more sharply in 2019, when full-paced machine assembly gets underway and each component must be available in a precisely orchestrated sequence.

INTERNATIONAL PROJECT MANAGEMENT: staying on track for success

To have confidence that the ITER Project is on track for success requires an understanding of the organizational reforms we put in place starting three years ago, the external validation of those reforms, and our performance in relation to agreed milestones.

Initial reforms: In early March 2015, when I took over as ITER Director-General, the organizational deficiencies and management shortcomings of the project were well understood, based on a probing and critical 2013 Management Assessment led by the American expert Bill Madia of Stanford University. The pace of improvement immediately following the 2013 report, however, remained unsatisfactory. My agreement to take on the role of Director-General, after extensive consultation, was contingent on the acceptance by all ITER Members of the Action Plan I mentioned in my introduction today, which I proposed at the time as the way to get the project back on track.

The positive impacts of the Action Plan were rapidly evident. The ITER reorganization that followed created a structure, decision-making protocol, and modes of interaction more suited to this complex, first-of-a-kind project. The Executive Project Board, made up of myself, my two deputies, and the heads of each of the seven Domestic Agencies, has proven effective in resolving the technical questions that arise naturally at the interface of the ITER systems and components contributed by each Member. The Reserve Fund we set up remains an efficient mechanism for financing timely adjustments to the design where necessary. The design finalization for critical path components has been a vital step to prevent further delays and cost overruns. And cross-organizational Project Teams, including all relevant actors in a single entity, have been used to guide progress on the most critical project elements.

By late 2015, after eight months of exhaustive technical analysis and consultation with Domestic Agencies and suppliers, we had successfully compiled a fully integrated schedule with associated resource projections. The cost increases and longer timeline of the new schedule were, in retrospect, inevitable: because previous schedules and cost estimates had been based more on externally imposed conditions rather than on a realistic technological basis and an integration of Members' constraints. The "Best Technically Achievable Schedule" we presented to the ITER Council in November 2015 reflected a comprehensive understanding of a machine with more than 1 million components and correspondingly complex manufacturing, construction and assembly sequences. The integrated analysis that led to this schedule was the essential foundation to give confidence that the ITER Project would be able to progress forward on a realistic and reliable basis, if all Members continued to meet their commitments.

The ITER Council at that time acknowledged the much-improved understanding of project scope, sequencing, risks, and costs achieved by this systematic review. It expressed appreciation for the tangible progress in construction and manufacturing. And it called for an independent review of the overall proposed schedule and associated resource estimates, to validate our methodology and analysis, to suggest adjustments and improvements where warranted, and if possible to identify additional measures for consolidating and expediting the schedule and reducing costs.

External review and validation: In April 2016, when I appeared before this Committee, we had just received the report of the independent ITER Council Review Group, the first time our efforts had received an intensive review by an external body. The Review Group, consisting of 14 international experts, had as chartered conducted a thorough examination of our proposed schedule and resource estimates, and found both to be credible and realistic—although extremely challenging. Based on an intensive drill-down into the project details, they also reported that the project reform efforts had resulted in "substantial improvement in project performance, a high degree of motivation, and considerable progress." They found that collaboration between the ITER Organization and the Domestic Agencies had markedly improved, but still called for "further strengthening" of these internal relationships in a "culture of collaboration"—a recommendation that, as you have seen, we wholeheartedly embraced.

One month later, we received a second significant element of external validation, when the Secretary of Energy reported to Congress with positive statements regarding progress of the project. The Secretary concluded that "ITER remains the best candidate today to demonstrate burning plasma, which is a necessary precursor to demonstrating fusion energy power." The Secretary recommended that the U.S. should remain a partner in the project through FY 2018, but should re-evaluate continued participation prior to the FY 2019 budget submittal.

While as I noted earlier we believe strongly that continued U.S. participation is in the mutual interest of both ITER and the United States, we welcomed this continued scrutiny of project performance. Since that time, we have had regular semi-annual independent reviews by some of the leading world experts on topical issues. In June 2017, we received the report of an independent review of ITER's approach to Risk Analysis and Risk Management. In November 2017, a second review was completed focused on our processes for defining and freezing the design interfaces of the systems, structures and components required for First Plasma. The latest Management Assessment, led by Japan, was also completed in 2017.

Both the Risk Management and Interface Freezing reviews have compared the ITER Project to industry standards, recognized best practices, and best available techniques—while also accounting for ITER's first-of-a-kind nature, which in some cases requires even more sophisticated measures than in past industrial projects. Each of these reviews, as well as the 2017 Management Assessment, has validated ITER's progress and approaches to critical aspects of project management, finding that the project is well-managed, to the best industry standards. Each external assessment and review has also helped us to identify additional refinements of our methods. A new semi-annual external review has begun recently, focused on Configuration Management, and we look forward to receiving the results of that review in the coming months.

Project management and the achievement of a project culture: Changing the culture of a project does not occur overnight. At ITER it has taken us more than two years, and we have continued a rigorous emphasis on self-examination and ongoing improvement. To solidify the gains we made during project reforms, we have emphasized a disciplined approach to applying the best principles of international project management, risk management, systems engineering, and ultimately nuclear safety culture and project culture. Adhering to the revised schedule has not in any sense been automatic or easy; it has required a systematic anticipation and mitigation of risks as well as day-by-day integration and teamwork. Developing and implementing an Earned Value Management system has been a key asset in this regard. And the incorporation of recognized systems engineering best practices has improved the rigor of verifying and validating that safety, quality, and technical performance criteria are incorporated across the full spectrum of construction and manufacturing activities.

Performance to agreed milestones: In November 2015, when we first presented our proposed schedule through First Plasma in 2025, the ITER Council emphasized the importance of maintaining rapid momentum in construction and manufacturing even while external reviews and validation processes were ongoing. For this reason, the Council approved the proposed schedule for 2016-17, together with a set of 29 well-defined technical and organizational milestones covering this two-year period, referenced to this schedule and the hierarchy of associated project activities. These milestones could be used to monitor our ongoing reliability and progress; if achieved successfully and on time, it would demonstrate that the ITER Project was keeping pace.

A full set of additional milestones have since been formulated covering the entire period through the realization of First Plasma in 2025. I am pleased to report that, to date, 31 milestones have been successfully achieved. Two of the milestones for 2016-17, both related to civil works in the Tokamak Building, have been decided to be postponed several months ago; in both cases, scheduling sequences have been re-adjusted and mitigation measures put in place to ensure this slippage will not affect the overall schedule. All aspects of the critical path schedule remain on track.

These positive results should in no way be taken for granted; they represent collective effort and teamwork across all project partners, including supplier companies and laboratories. While we have experienced challenges and potential delays with individual milestones, we have in each case mitigated those challenges, offset or reduced the risk of delays and gotten back on track. Overall, so far, there has been no slippage whatsoever in the reference schedule. This reflects substantial improvements in our collective capacity for anticipating and mitigating emergent risks.

Establishing an updated baseline: Following our initial November 2015 presentation of the revised schedule through First Plasma, the ITER Council asked us to initiate a further series of discussions with all ITER Members. The intent was to incorporate the proposed schedule and resource projections into an agreed overall project baseline that would extend through Deuterium-Tritium (DT) full fusion power operation. These discussions were needed to consider the priorities and resource constraints of ITER Member governments, as well as the manufacturing schedules and the interfaces of each Member's in-kind contributions.

The culmination of this schedule iteration was reached one year later, in November 2016, when the ITER Council approved the Overall Project Schedule through First Plasma in 2025 and onward to Deuterium-Tritium (DT) full fusion power operation in 2035. The associated Overall Project Cost was approved *ad referendum,* meaning that it required final consideration by ITER Member governments. For the United States, the Department of Energy subsequently approved the Overall Project Cost in January 2017.

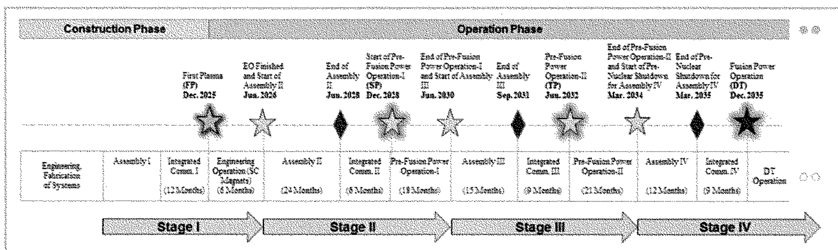


Figure 17: Schematic of the 4-stage strategy from First Plasma to DT operation within the revised ITER baseline.

Putting all of these elements together into an Updated Project Baseline represents a pivotal project-wide achievement, once again requiring integration and teamwork to accommodate the resource constraints of all ITER Members. The result, as depicted in Figure 17, is a 'staged approach' between First Plasma and Deuterium-Tritium Operation.

The staged approach envisages several assembly phases and plasma operation campaigns, in keeping with when ITER Members will be in a position to deliver the associated equipment. In advance of First Plasma, the core tokamak systems will be assembled with the necessary auxiliary systems (heating and current drive (H&CD), diagnostics, fuelling) required to support plasma breakdown. This is consistent with First Plasma as a demonstration of the successful integration of the tokamak core and principal plant systems (power supplies, cooling, cryogenics, vacuum, etc.) and will conclude the first phase of integrated commissioning of the ITER facility.

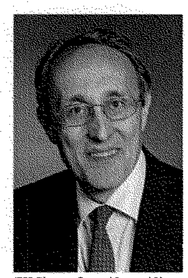
Subsequently, the magnet systems will be commissioned to full current, and the full set of in-vessel components (including shielding blanket, first wall and divertor) will be installed, together with an expanded subset of the heating and current drive and diagnostic capability. The first physics experiment is planned in December 2028. Two periods of experimental operation with hydrogen and helium plasmas will follow, with a 3rd assembly period to complete the H&CD systems and most of the remaining diagnostic capability. These two experimental periods will commission all tokamak and auxiliary systems with plasma, and will demonstrate full technical performance of the ITER device before the transition to D and DT operation in the 4^{th} stage of the experimental program.

CONCLUSION

At the ITER Organization, we are committed to ensuring the delivery of the ITER machine on time and the full achievement of the associated scientific and technological benefits, as the launching pad for the eventual commercial deployment of fusion-generated electricity. We are committed to delivering the project in a manner that lives up to the trust placed in us by all ITER Members. We are committed to continuous improvement, to make ITER the model for international collaboration on complex science and technology challenges. And we are committed to making ITER a sound investment for the U.S., as for all our partners. These commitments require that all of the seven ITER partners fulfil their own commitments towards the ITER project by providing the needed resources on time (staff, in-kind components and in-cash contribution). This year is critical on this point, since some Members seem not prepared to do so for the first time. We look forward to a long and fruitful collaboration.

Thank you for this opportunity.

Bernard Bigot, Director-General ITER Organization



ITER Director-General Bernard Bigot

On 5 March 2015, the ITER Council appointed Bernard Bigot, from France, Director-General of the ITER Organization.

Bernard Bigot has been closely associated with ITER since France's bid to host the project in 2003. Following the ITER site decision in 2005, the signature of the ITER Agreement in 2006 and its ratification by all Members in 2007, Mr Bigot was delegated by the French government to act as High Representative for the implementation of ITER in France, a position that he has occupied since 2008.

With the responsibility of coordinating the realization of ITER and ensuring the representation of France to the ITER Members and the ITER Organization, he has followed the project for some twenty years.

In his long and distinguished career, Bernard Bigot has held senior positions in research, higher education and government. Prior to his appointment at ITER he completed two terms (2009-2012 and 2012-2015) as Chairman and CEO of the French Alternative Energies and Atomic Energy Commission, CEA. This government-funded technological research organization—with ten research centres in France, a workforce of 16,000 and an annual budget of EUR 4.3 billion— is active in low-carbon energies, defense and security, information technologies and health technologies.

From 2003 to 2009 Bernard Bigot served as France's High commissioner for atomic energy, an independent scientific authority whose mission is to advise the French President and the French government on nuclear and renewable energy policy and in all the other scientific and technological domains where the CEA intervenes.

On his long experience in the field of energy, he says: "*I've always been concerned with energy issues. Energy is the key to mankind's social and economic development. Today, 80 percent of the energy consumed in the world comes from fossil fuels and we all know that this resource will not last forever. With fusion energy we have a potential resource for millions of years. Harnessing it is an opportunity we cannot miss.*"

Bernard Bigot was trained at the Ecole normale supérieure de Saint-Cloud and holds an *agrégation* (highest-level teaching diploma in France) in physical science and a PhD in chemistry. He is a high-ranking university professor (*classe exceptionnelle*) at the Ecole normale supérieure de Lyon, which he helped to establish and which he directed from 2000 to 2003. Author of over 70 publications in theoretical chemistry, Bernard Bigot was also in charge of research at the Ecole normale supérieure and Director of the Institut de recherche sur la catalyse, a CNRS laboratory specializing in catalysis research.

In parallel to these academic responsibilities, he worked at the ministerial level as Head of the Scientific and Technical Mission (1993-1996), Director-General of Research and Technology (1996-1997), and Deputy Director for Research from 1998 to 2000.

In 2002, Bernard Bigot was appointed Principal Private Secretary to the Research and New Technologies Minister and Assistant Private Secretary to the Minister for Youth, Education and Research. It was during his tenure in this office that France proposed a site in Cadarache (southern France) to host the ITER Project.

Bernard Bigot is a *Commandeur* in the French Order of the Legion of Honour, a *Commandeur* in the Royal Swedish Order of the Polar Star, and an *Officer* the French Order of the National Merit. In October 2014 he received the Gold and Silver Star in the Japanese Order of the Rising Sun.

Chairman WEBER. Thank you, Dr. Bigot.
Dr. Van Dam, you're recognized for five minutes.

TESTIMONY OF DR. JAMES W. VAN DAM, ACTING ASSOCIATE DIRECTOR, FUSION ENERGY SCIENCES, OFFICE OF SCIENCE, DEPARTMENT OF ENERGY

Dr. VAN DAM. Thank you, Chairman Weber and Ranking Member Lofgren in place of Ranking Member Veasey, and also full Committee Chair Smith, my former Congressman from Austin, Texas, and other distinguished Members of the Subcommittee. Thank you for this invitation to testify before you today about fusion energy research.

I am currently the Acting Associate Director for the Office of Fusion Energy Sciences, and I appreciate this opportunity to review the status of fusion research and describe programmatic directions going forward.

The mission of the Fusion Energy Sciences, or FES, program is to expand the fundamental understanding of matter at very high temperatures and densities and to build a scientific foundation needed to develop a fusion energy source. This is accomplished through the study of plasma called the fourth state of matter, which is wide-ranging since 99 percent of the visible universe is plasma.

The FES program addresses several Administration research and development priorities. Fusion research has the potential to contribute to American energy dominance by making available a robust, clean baseload electricity technology. Plasma science can contribute to American prosperity through the potential for spinoff applications, establish partnerships within and outside DOE and increase our research effectiveness, and we also help train a STEM-focused workforce in key areas of technological and economic importance, as well as national security.

The DIII–D National Fusion Facility at General Atomics and the National Spherical Torus Experiment Upgrade, NSTX–U, at Princeton Plasma Physics Laboratory, are world-leading Office of Science user facilities. The DIII–D scientific team has 439 researchers from 49 U.S. institutions, plus another 164 researchers from 46 institutions and seven other countries. The DIII–D scientific results are recognized worldwide.

NSTX–U is the world's highest-performance spherical tokamak, a magnetic configuration invented in the United States with attractive advantages of compactness and component testing. NSTX–U is currently not operating while its magnetic coils are being repaired.

The United States is a world leader in fusion theoretical modeling and high-performance computer simulations. FES supports eight multi-institutional Scientific Discovery through Advanced Computing, SciDAC, centers jointly with the Advanced Scientific Computing Research Program Office. Fusion researchers also lead one of the Office of Science exascale computing projects.

Several multi-institutional U.S. teams conduct research under international partnerships on superconducting tokamaks and stellarators with long-duration capabilities not available in the United States. To test fusion materials under extreme conditions, the fiscal year 2019 budget request proposes a linear diverter simulator facility with world-leading capabilities.

Under the U.S. contributions to ITER construction project, we are fabricating several hardware systems. One is the central solenoid, which will be the world's largest superconducting pulsed electromagnet, the so-called heartbeat of ITER. The U.S. First Plasma subproject is halfway finished. The United States has spent $1 billion, 90 percent of which is within the United States through approximately 600 contracts in 44 States.

The U.S. ITER project is very well-managed. The ITER Organization has significantly improved its project management under Director-General Bigot, and we thank him. The construction progress onsite is very substantial.

FES also supports discovery plasma science through partnerships with the National Science Foundation and DOE's National Nuclear Security Administration. U.S. scientists are world leaders in inventing new plasma measurement techniques.

Strategic directions going forward for the FES program are informed by several planning efforts, including priorities described in the document, "The Office of Science's Fusion Energy Science Program: A 10–Year Perspective;" research opportunities identified in recent community workshops, one of which was led by Dr. Wade; reports from the Fusion Energy Sciences Advisory Committee; and reports from the National Academy of Sciences. Currently, a National Academy study on the strategic plan for U.S. burning plasma research is underway. Dr. Herrmann is one of the panel members. And also the National Academy is now launching the 2020 Plasma Decadal Survey.

Thank you for this opportunity today to describe DOE's research efforts in Fusion Energy Sciences research, and I look forward to discussing this topic with you and answering your questions. Thank you.

[The prepared statement of Dr. Van Dam follows:]

TESTIMONY OF DR. JAMES VAN DAM

ACTING ASSOCIATE DIRECTOR, OFFICE OF FUSION ENERGY SCIENCES

OFFICE OF SCIENCE, U.S. DEPARTMENT OF ENERGY

BEFORE THE

COMMITTEE ON SCIENCE, SPACE AND TECHNOLOGY

SUBCOMMITTEE ON ENERGY

U.S. HOUSE OF REPRESENTATIVES

MARCH 6, 2018

Chairman Weber, Ranking Member Veasey, and Members of the Subcommittee, thank you for the invitation to testify before you today on fusion energy research. I appreciate this opportunity to review the status of research in this scientific area and to describe programmatic directions going forward.

Mission:
The mission of the Fusion Energy Sciences (FES) program is to expand the fundamental understanding of matter at very high temperatures and densities and to build the scientific foundation needed to develop a fusion energy source. This is accomplished through the study of plasma, often called the fourth state of matter, and how it interacts with its surroundings.

Plasma science is wide-ranging, since 99% of the visible universe is composed of plasmas of various types. High-temperature fusion plasmas at hundreds of millions of degrees occur in national-security applications, albeit for very short times. The same fusion plasmas could be exploited in the laboratory in a controlled fashion to become the basis for a future clean nuclear power source, which will provide domestic energy independence and security. This is a large driver for the FES subprograms focused on the scientific study of "burning plasma." In the burning plasma state of matter, the nuclear fusion process itself provides the dominant heat source for sustaining the plasma temperature. Such a self-heated plasma can continue to undergo fusion reactions that produce energy, while requiring little input of heating power from the outside resulting in large net energy yield.

Administration R&D priorities and FES

The FES program addresses several of the Administration's research and development budget priorities. Research in fusion has the potential to contribute to American energy dominance by making available to the American people a robust, clean base-load electricity technology that relies on widely available and virtually inexhaustible fuel sources. Research in plasma science, within and beyond fusion, will contribute to American prosperity through the tremendous potential for spinoff applications as well as targeted investments in early-stage low temperature plasma research that has the potential to lead to the development of transformative technologies. Investments in our major fusion facilities and smaller-scale experiments will help maintain and modernize our research infrastructure for continuing to conduct world-leading research. Established partnerships within and outside DOE maximize leverage and increase the cost-effectiveness of FES research activities. Finally, the unique scientific challenges and rigor of fusion and plasma physics research lead to the development of a well-trained STEM-focused workforce, which will contribute to maintaining and advancing U.S. competitiveness and world leadership in key areas of future technological and economic importance, as well as national security.

Status of FES research

The FES program is organized into four subprograms: (1) *Burning Plasma Science--Foundations*, (2) *Burning Plasma Science--Long Pulse*, (3) *Burning Plasma Science--High Power*, and (4) *Discovery Plasma Science*

In the ***Burning Plasma Science--Foundations subprogram***, the behavior of laboratory fusion plasmas confined with strong magnetic fields is investigated. The DIII-D National Fusion Facility and the National Spherical Torus Experiment-Upgrade (NSTX-U) are world-leading Office of Science (SC) user facilities for experimental research available to and used by scientists from national laboratories, universities, and industry research groups.

- **DIII-D** (operated by General Atomics) is a world-class tokamak facility. This facility is highly flexible, with extensive diagnostics to measure plasma behavior. The DIII-D scientific team consists of 439 researchers from 49 institutions in the U.S. and 164 researchers from 46 institutions across seven other countries. These numbers include 64 postdoctoral researchers, 75 graduate students, 13 Master's degree students, and 21 undergraduates.

  DIII-D plans to operate 18 run weeks in FY 2018 and then go into a facility outage (called Long Torus Opening) for facility enhancements. The Long Torus Opening is planned to extend into the first part of FY 2019, after which the machine will resume operation for 12 weeks. The scientific results from DIII-D for magnetic confinement fusion research are highly recognized worldwide. Additionally, during FY 2017, FES supported a new initiative to carry out experiments on DIII-D for basic plasma science, not directly related to fusion energy issues; this successful initiative will be repeated in FY 2018.

- **NSTX-Upgrade** (operated by PPPL) is the world's highest performance spherical tokamak, a magnetic confinement configuration invented in the U.S, which has the attractive advantages of compactness and component testing. NSTX-U is currently not operating, due to a magnetic coil failure and other hardware issues.

  During FY 2017, PPPL conducted an extensive series of reviews to identify the design, construction, and operational deficiencies of the facility. The laboratory has developed an integrated corrective action plan for repair and recovery of reliable experimental operation. The lab is currently formulating a baseline. SC is conducting an internal assessment of the recovery scope, the mission need, and the laboratory's capabilities. By the end of the year, cost and schedule implications will be in hand.

Complementing these experimental activities is a world leadership effort in fusion theoretical modeling and high-performance computer simulations to predict and interpret the complex behavior of plasmas as self-organized systems. As part of this effort, FES supports eight Scientific Discovery through Advanced Computing (SciDAC) centers, involving scientists from 11 universities, 8 DOE laboratories, and 5 industry R&D groups. Seven of these SciDAC centers are supported in partnership with the Advanced Scientific Computing Research (ASCR) program office. The FES SciDAC centers were re-competed in FY 2017. In addition, scientists from PPPL lead a national team working on whole-device modeling of magnetically confined fusion plasmas, which is one of the 22 ASCR-funded Exascale Computing Projects.

In the ***Burning Plasma Science--Long Pulse subprogram***, FES investigates the behavior of plasmas that are confined near steady state. U.S. scientists take advantage of international partnerships to conduct research on superconducting tokamaks and stellarators with long-duration capabilities that are not available in the U.S. This includes:

- Three multi-institutional teams of U.S. researchers carry out collaborative research on the long-pulse tokamak facilities in China and Korea.
- Another multi-institutional U.S. team cooperates in research on the new superconducting stellarator facility in Germany.
- Other teams work on several other overseas experimental facilities that are not superconducting but have unique capabilities.
- A useful recent development is the establishment of remote collaboration/connectivity centers (e.g., at GA, PPPL, and MIT) that allow U.S. scientists to participate and lead experiments on overseas facilities, thus reducing the need for travel and creating collaboration efficiencies.

In addition, the development of novel materials, a research area of high interest to many scientific fields, is especially important for fusion energy sciences since fusion plasmas create an environment of high-energy neutrons and huge heat fluxes that impinge on and damage the material structures containing the plasmas. The FY 2019 budget request proposes to initiate design and some fabrication activities for a new linear divertor simulator facility that will have world-leading capabilities to test materials under extreme-heat-flux fusion conditions.

The ***Burning Plasma Science--High Power subprogram*** refers to the frontier scientific area of the actual creation of strongly self-heated fusion burning plasmas, which will allow the discovery and study of new scientific phenomena relevant to fusion as a future energy source.

Currently the Burning Plasma Science--High Power subprogram is focused on the U.S. Contributions to ITER, a construction project. ITER is a large, international project, involving the U.S., European Union (EU), Russia, China, Japan, India, and South Korea, which aims to construct a full-scale experimental fusion reactor, located in southern France, about 50 miles north of Marseille. In 2007, the ITER project was scheduled to be complete (i.e., achieve deuterium-tritium burn) by 2016, with the U.S. share, at that time, approved to be $1.1 billion. To date, U.S. in-kind contributions to ITER have been $1.06 billion. Under the present schedule approved by the ITER Organization, ITER will achieve the first-plasma milestone in 2025-26 and be complete (achieve D-T burn) in 2035. The U.S. cost is presently estimated to be $4.7-6.5 billion.

The U.S. is responsible for delivering a number of hardware systems, which are being fabricated by industries, national laboratories, and universities in the U.S. The largest of these U.S. hardware systems are the seven modules for the central solenoid magnet of ITER, which when completed will be the world's largest superconducting pulsed electromagnet - the so-called "heartbeat of ITER." The First Plasma subproject of the U.S. Contributions to ITER project is more than halfway complete. Fabrication of the ITER central solenoid magnet assembly, which is the U.S.'s highest-priority activity, is, as of January 2018, 68% complete.

So far, slightly more than $1B has been spent, with more than 90% of the U.S. ITER funding for hardware systems spent within the U.S., through more than 600 contracts in 44 states. Two hardware systems were completed and delivered in 2017: the Steady-State Electrical Network for the ITER site, and the superconducting conductor for the ITER toroidal field coils. (Detailed information about the U.S. ITER fabrication activities is contained in the four graphs attached to this testimony.) The U.S. Contributions to ITER project is efficiently and effectively managed by the U.S. ITER Project Office at ORNL in partnership with PPPL and SRNL (cf. supplemental attached pages). The subject of continued U.S. participation in the ITER project is included in the Administration's ongoing civil nuclear review.

The ITER Organization in France has very significantly improved its project management since the appointment of the current Director General, Dr. Bernard Bigot, in 2015. Construction progress on the ITER site is quite substantial. In December 2017, the ITER Organization celebrated 50% completion to First Plasma, as reported in many media outlets.

The FES ***Discovery Plasma Science subprogram*** involves research in areas such as plasma astrophysics, high energy density laboratory plasmas (HEDLP), and low temperature plasmas. Some of this research is carried out through a partnership on basic plasma science and engineering with the National Science Foundation (NSF) and a joint program on high energy density laboratory plasmas with the National Nuclear Security Administration (NNSA). A few examples of Discovery Plasma Science research programs are the following:

- The Large Area Plasma Device at the University of California, Los Angeles is a world-unique device for simulating the behavior of plasma-loaded magnetic field lines. One such ubiquitous behavior is called reconnection, when magnetic field lines rip apart and reconnect—which occurs in the Earth's magnetic field due to the solar wind, in solar flare eruptions, in the formation of astrophysical neutron stars and black holes, and in laboratory fusion plasmas.
- Recently FES solidified the U.S. leadership in reconnection physics by funding an intermediate-scale, integrated, collaborative science user facility at the University of Wisconsin-Madison.
- FES has supported a multi-institutional plasma science center that performs early-stage research on the detailed dynamics of low-temperature plasmas, which have future spin-off applications.
- The Matter in Extreme Conditions instrument, one of six end stations at the Linac Coherent Light Sources user facility at SLAC National Accelerator Laboratory, is a world-leading facility for the study of high energy density plasmas, which underlies the understanding of laser-plasma interactions, astrophysical processes, and inertial confinement fusion. Some recent highlights are the production of "diamond rain" (predicted to occur in the interior of Icy Giant Planets) and the discovery of a new form of water that is simultaneously solid and liquid.
- Plasma techniques are being used to capture and cool anti-hydrogen atoms at CERN so that experiments can be performed that might explain why there is so little anti-matter in the universe.

Also, U.S. scientists are world leaders in the invention and development of high-resolution plasma measurement techniques. One such example is the x-ray crystal spectrometer, a versatile diagnostic that has been utilized on several different magnetic confinement fusion facilities and, more recently, on inertial confinement facilities.

Strategic directions going forward for the FES program are informed by several sources, including the following:

- The priorities described in the document "The Office of Science's Fusion Energy Sciences Program: A Ten-Year Perspective" (submitted by DOE to Congress in December 2015): These priorities include keeping SC fusion user facilities world-leading, investing in high performance computing and preparing for Exascale, supporting high-impact research in fusion materials, strengthening partnerships for access to international facilities with unique capabilities, learning how to predict and control transient events in fusion plasmas, and continuing stewardship of discovery plasma science (e.g., via intermediate-scale basic facilities).
- The research opportunities identified in a series of four community engagement workshops held in 2015, whose written reports were finalized in 2016 and are available online.[1]

[1] https://science.energy.gov/fes/community-resources/workshop-reports/

- Other community interactions: In recent years, the fusion community self-organized to hold several workshops: a stellarator research opportunities conference, two workshops to provide input to the National Academy of Sciences (NAS) burning plasma study, three high energy density science workshops, and an exascale computing requirements workshop.
- Reports from the Fusion Energy Sciences Advisory Committee (FESAC), a federal advisory committee chartered under the Federal Advisory Committee Act: Two recent examples are the (1) the 2016 FESAC report[2] that describes how plasma science advances have led to spinoff applications and enabling technologies with considerable economic and societal impact for the American quality of life, and (2) the 2018 FESAC report about the potential for transformative enabling capabilities in fusion science and technology that could accelerate progress toward fusion energy.
- Reports from the NAS: Currently, the NAS is performing a study entitled "A strategic plan for U.S. burning plasma research," which was requested by SC. This study released an interim report on December 21, 2017; its final report is expected toward the end of 2018. Another NAS study, soon to be launched, is the Plasma Decadal Survey. This Survey has multiple federal sponsors, including DOE, NSF, and the Department of Defense, and its report is expected in 24 months. The two previous Plasma Decadal Survey reports from NAS have been influential. In addition, the NAS recently released a report on Intense Ultrafast Lasers[3], which is of high interest to the part of the FES program for research on high energy density laboratory plasmas.

In conclusion, the FES program is actively engaged at the forefront of fundamental research in burning plasma science and discovery plasma science, with the use of domestic facilities and through international partnerships. Thank you for the opportunity to come before you today to describe DOE's efforts in fusion energy sciences. I look forward to discussing this topic with you and answering your questions.

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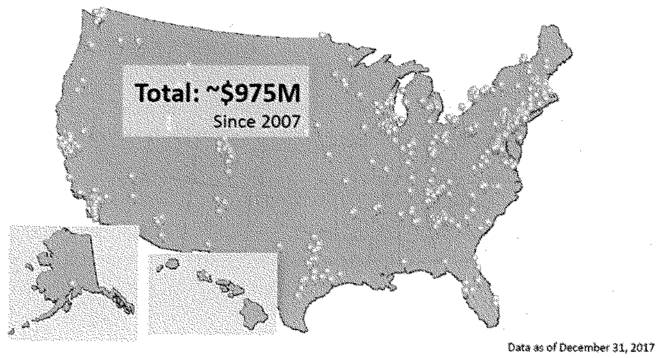
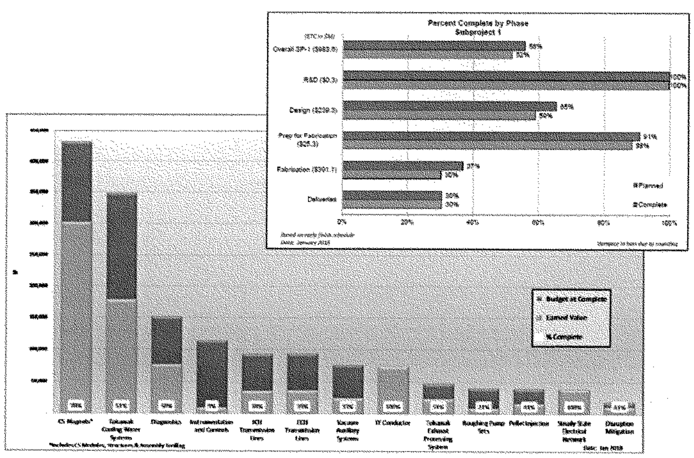
[2] https://science.energy.gov/~/media/fes/fesac/pdf/2015/2101507/FINAL_FES_NonFusionAppReport_090215.pdf
[3] https://www.nap.edu/catalog/24939/opportunities-in-intense-ultrafast-lasers-reaching-for-the-brightest-light

Over 80% of Awards and Obligations Remain in the US

- 600+ contracts awarded to US industry and universities, and obligated to DOE national laboratories in 44 states
- 500+ direct jobs and 1100+ indirect jobs created or maintained per year

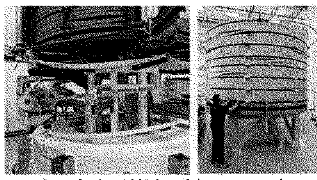


Progress of US ITER Subproject 1

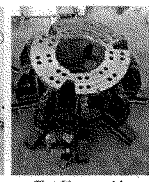


Examples of US hardware for ITER

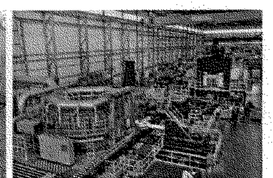
First Plasma Subproject deliveries 30% complete



Central solenoid (CS) modules are in serial fabrication at General Atomics' Poway, CA facility.



The CS assembly platform was delivered in 2017.

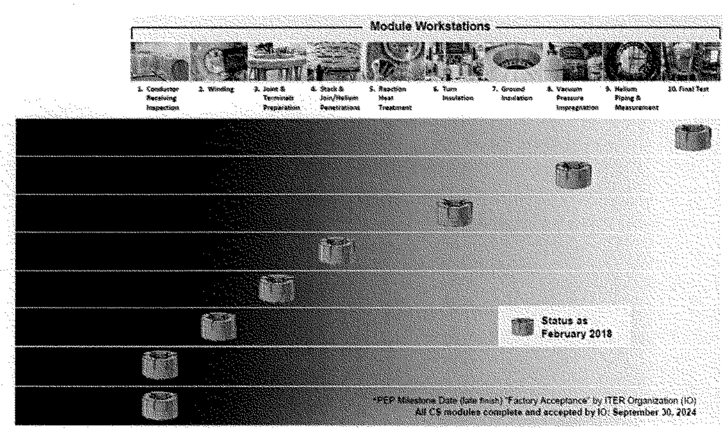


Piping fabrication for the Tokamak Cooling Water System is underway at Schulz XP in Robinsonville, MS

US completed Toroidal Field Coil Conductor deliveries and acceptance in 2017.

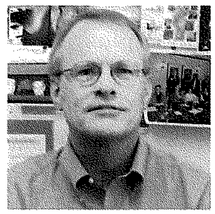
US completed delivery of Steady State Electrical Network components to the ITER site in 2017.

Central Solenoid Module Fabrication Progressing



Brief Biography

JAMES W. VAN DAM



Dr. Van Dam is serving as acting associate director of the USDOE Office of Science for the Fusion Energy Sciences program since August 2017. Prior to that, he was the research division director for the Fusion Energy Sciences program since September 2011.

During 1980-2011, he was a research scientist, associate director, and for nine years director of the Institute for Fusion Studies at The University of Texas in Austin.

During 2007-2011, he was also director of the U.S. Burning Plasma Organization and chief scientist for the U.S. ITER Project Office.

He is a Fellow of the American Physical Society (Division of Plasma Physics). He has been the organizer for numerous workshops and several international symposia, a visiting scientist/professor at several laboratories and universities, thesis advisor for graduate students, a member of various national committees, journal editor, and a consultant to industry. He has published over 100 scientific papers and two books.

After graduate study at University of California-Berkeley and the Institute of Plasma Physics (Japan), he completed his Ph.D. at UCLA and then was a postdoc at the Institute for Advanced Study (Princeton) before moving to the University of Texas.

Chairman WEBER. Thank you. Dr. Wade, you're recognized for five minutes.

TESTIMONY OF DR. MICKEY WADE, DIRECTOR OF ADVANCED FUSION SYSTEMS, MAGNETIC FUSION ENERGY DIVISION, GENERAL ATOMICS

Dr. WADE. Thank you, Mr. Chairman. I would like to thank the Committee for this opportunity to share my views on the U.S. fusion program. I'd like to stress that these are my views and not necessarily those of my employer.

I have spent nearly 30 years working in fusion research, 15 of those at Oak Ridge National Lab, and the last dozen at General Atomics. I'm passionate about fusion energy and maybe as importantly about the role the United States can play in its development.

This marks the 80th anniversary of the discovery of the process the powers our sun and stars, nuclear fusion. We've made remarkable progress over the intervening 80 years in figuring out how to harness the enormous potential of fusion energy. The United States has been at the forefront of this progress, forging a path that has taken fusion energy from a dream to a potential energy source for thousands of years. Critics can no longer say that fusion is 50 years away and always will be.

As we've just heard from Dr. Bigot, the first phase of the—of construction of the most ambitious fusion project ever undertaken, ITER, is now 50 percent complete. In 2025, a little over seven years from now, ITER will produce its First Plasma. Just ten years later, ITER will begin an operations phase that will produce powerplant levels of fusion power for the first time.

Anticipating this, other nations are increasing their emphasis on fusion energy, putting together strategic plans to capitalize on ITER's success. Private enterprises are now evaluating high-risk, outside-the-box approaches to fusion energy. Yet as excited as I am about this future, I'm very concerned that our nation's commitment to fusion is wavering and the decisions our country is making now will relegate us to the sidelines in the future. U.S. participation in ITER is in question. Investment in U.S. fusion capabilities is being far outpaced by other nations, particularly China. The United States does not have a comprehensive strategic plan for fusion development.

The United States has long been a world leader in fusion energy research, and this continues today. U.S. scientists continued to discover new phenomena and develop pioneering solutions to fusion's challenges. The United States is building the ITER central solenoid. When fully assembled, it will be nearly as wide as this table, nearly as tall as this building, and be the most powerful electromagnet in the world. It will be the heart of ITER, enabling ITER to generate plasma temperatures that exceed 150 million degrees, about 10 times the temperature of the sun.

So what needs to be done? I offer two recommendations for your consideration. Number one, the United States should make a firm commitment to fully fund the ITER project. The early days of ITER were very challenging, but it appears the ship is now sailing in calm waters thanks to the efforts of Dr. Bigot and the ITER members. I believe ITER is our ticket to be a tier-one player in fusion development, giving us full access to the preeminent fusion facility in the world for only nine percent of the fusion project cost. Over 80 percent of these contributions are for in-kind projects built in the United States, creating jobs and associated expertise here. On the flip side, withdrawing from ITER could isolate U.S. scientists from the international effort and would require a new U.S. approach to study burning plasma with an unknown time horizon and cost.

Number two, the United States should move now to establish a comprehensive strategic plan that seeks to capitalize on ITER's success. Fusion energy should be called out in a national energy policy. A strategic plan with clearly defined technical objectives should be developed that sets the United States on an aggressive distinctive pathway to fusion energy. This pathway should include new investment in world-class research capabilities that will attract and engage the best U.S. minds from universities, national labs, and the private sector. Following through on initiatives, evaluating new ideas, and developing transformational technologies will all be required in arriving at the most cost-attractive approach for fusion development.

In 1962, at the beginning of the Apollo program, President John F. Kennedy issued a proclamation that I think speaks in to this hearing today. He said, and I quote, "We choose to do these things not because they are easy but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one we intend to win." Less than seven years later, an American walked on the moon. It's in the American DNA to take on the grandest challenges and not just succeed but be the best. Fusion is one of those grand challenges.

I hope you will join us in forging a path that ensures the United States is a world leader in making fusion energy a reality for future generations. Thank you for the opportunity to speak with you today. I look forward to your questions and working with you in the future.

[The prepared statement of Dr. Wade follows:]

Written Testimony of Mickey Wade, Ph.D.
Director, Advanced Fusion Systems, General Atomics

Delivered before the
Subcommittee on Energy
Committee on Science, Space and Technology
U.S House of Representatives

The Future of U.S. Fusion Energy Research
March 6, 2018

I would like to thank the Committee for this opportunity to share my views on the status and future prospects of the U.S. fusion program. I want to stress that these are my own views and do not necessarily reflect the views of my employer.

The U.S. and the world have made enormous progress toward achieving fusion energy, putting within our grasp major milestones that will demonstrate the feasibility of fusion energy. ITER construction for First Plasma is now over 50% complete and initial operation of the facility is planned for 2025, just seven years from now. In addition, ITER plans to begin an experimental campaign in 2035 that will demonstrate a 'burning plasma', a key moment in the realization of fusion energy wherein a self-heated plasma will for the first time be created, sustained, and studied. With these milestones clearly in view, the world's magnetic fusion program is now progressing rapidly toward a major inflection point for fusion energy development. However, despite this progress and opportunity, the U.S. fusion program is at significant risk of losing its position as a world leader as other nations are expanding funding on fusion development while U.S. funding is in decline.

I have been engaged in magnetic fusion energy research for the past 30 years, both in the national and international arenas. This involvement has given me a keen appreciation of the promise offered, the challenges involved, and the opportunities presented by developing fusion as an energy source for the future. From these experiences and perspectives, I offer the following for consideration by this Committee:

- Fusion energy has the potential to provide enormous amounts – more than 10,000 years from known land resources – of base-load electricity that is virtually free of greenhouse gases and available to all nations of the world. *The extent of fusion's potential is unmatched by any other known energy source and therefore worth sizeable investment toward its development.*
- Successfully delivering fusion energy demands integration of several high-tech elements that span a wide range of scientific and engineering disciplines. It is unlikely that the required breadth of R&D can be undertaken by a single corporate entity; hence, *government sponsorship in the near-to-intermediate term is required to promote R&D activities over the full range of capabilities required for fusion energy.*
- *The U.S. fusion community is passionate about making fusion energy a reality and is leading the world research program in several key scientific areas.* This exciting, world-class research, carried out on world-class facilities, continues to place the U.S. in a

leadership role in the development of fusion energy (though that leadership is threatened due to large investments by other nations).

- Looking forward, burning plasma research is an essential element in the development of fusion energy as future fusion systems will rely on the production and sustainment of such plasmas. ITER will provide this platform for U.S. researchers. As the only existing project worldwide intended to create a burning plasma at the scale of a power plant, I believe *it is critical that the U.S. remain a party to the ITER project and position itself to exploit ITER by maintaining and acquiring expertise in critical technical areas through research on existing facilities, theory, and simulation.*
- Beyond ITER, significant opportunities exist for U.S. leadership in fields that enable realization of fusion energy (e.g., fusion nuclear materials) and/or development of more cost-attractive approaches to fusion energy (e.g., innovative confinement concepts, high-critical-temperature superconducting magnets). To capitalize on these opportunities, *the U.S. needs a vibrant domestic research program that can, alongside ITER participation, deploy leadership-class facilities and capabilities in these key research areas.*
- Strategically, the U.S. path to fusion energy is unclear at the moment, especially with funding trending downward. This stands in contrast to other ITER partners that have developed strategic plans structured to capitalize on ITER success to aggressively pursue fusion energy development. Our country's lack of commitment toward pursuing fusion aggressively puts us at risk of falling behind in the quest for fusion energy. In this regard, *the U.S. government should develop a clear policy on the importance of fusion energy as a national strategic interest and the role of fusion energy in national energy plan.*

During the rest of this testimony, I would like to offer my personal perspectives on these considerations, drawing from my experiences in the field, followed by some recommendations for this Committee to consider in developing legislation in the future.

Fusion Energy for the World's Future

The quest for fusion energy is here to stay. Fusion energy, the same process that powers the stars, offers the potential of a very compelling energy solution for the future with a readily available fuel supply, no greenhouse gas production, and the ability to serve as a large base-load supplier of electricity. The fuel for future fusion systems is abundant with estimates projecting over 10,000 years of availability from known land sources and significantly more if ocean resources are utilized. Future fusion systems will produce virtually no greenhouse gases, have no risk of uncontrolled meltdowns, and can be tailored to minimize the production of very-long-lifetime radioactive materials. Because of its promise, fusion energy will always motivate pursuit of solutions even though the development of fusion energy presents many significant technical challenges.

The potential of fusion is evidenced by the recent surge in the number of private startups evaluating innovative approaches to fusion energy. While this surge is indicative of emerging interest, it should be noted that these startups are focused heavily on developing high-risk, high-reward approaches to producing and confining fusion-grade plasmas, and therefore still require comprehensive programs for developing the full range of capabilities needed for fusion energy production. ITER, on the other hand, seeks to create and sustain a burning plasma using the most mature confinement configuration and demonstrated technologies, positioning it as a lower risk approach to the study of burning plasma science.

The science and technology of fusion requires state-of-the-art capabilities in a wide range of disciplines (e.g., plasma physics, materials, magnets, fuel cycle). Because the required technical capabilities are beyond those needed for other applications, fusion R&D must confront these challenges itself. In contrast, owing to fusion's interdisciplinary nature, many different fields of study have benefitted from fusion research. Spinoff technologies from fusion investments have had a transformative effect on society, with the public benefitting greatly from areas such as modern electronics, lighting, communication, manufacturing, and transportation.*

U.S. universities, labs, and industry have distinct leadership capabilities in the areas listed above with world-class researchers tackling the most challenging issues. However, the U.S. is not alone in this pursuit, with other nations (particularly the ITER Members) aggressively pursuing development of new capabilities that will further these disciplines while advancing fusion energy towards its development goal.

A major consideration for the time scale of fusion energy development is the observation that many economic models indicate a significant expansion of the world's electricity requirements in the latter half of this century. This is especially true for under-developed and/or emerging economies in which energy supply will likely pace economic growth and the quality of life in those countries. Because of this increasing need for clean energy sources and the short time scale involved, the U.S. has a distinct strategic interest in remaining a leader in energy technologies such as fusion. To this end, the U.S. needs to prepare for this opportunity now, putting in place the necessary technical know-how to position the U.S. at the forefront of future fusion development worldwide.

The U.S. Fusion Program

The U.S. program continues to be a world leader in the development of the scientific basis for fusion energy. This leadership is evidenced by the fact that U.S. researchers have been recognized for the Nuclear Fusion Prize† in 8 of the 13 years of the award for most impactful article in Nuclear Fusion, the top journal for publications of fusion research. In recent years, experiments on Alcator C-Mod (at MIT) and DIII-D (at General Atomics), motivated by U.S. theoretical studies, achieved record levels of normalized fusion performance that offer the potential of significantly improved fusion systems in the future. DIII-D has demonstrated scenarios that achieve the required level of ITER normalized performance in ITER-prototypical conditions, further increasing confidence that ITER will succeed in its mission.

These experimental findings are bolstered by detailed simulations in which U.S. scientists have modeled how small-scale fluctuations transport energy from the hot core to the edge in ITER, providing a much stronger scientific basis for projecting ITER's fusion power production. Scientists have also utilized emerging supercomputing capabilities to model how turbulence is spontaneously suppressed in the edge of tokamak plasmas leading to a factor of two increase in confinement quality, potentially solving a long-standing mystery of the field. All of these results

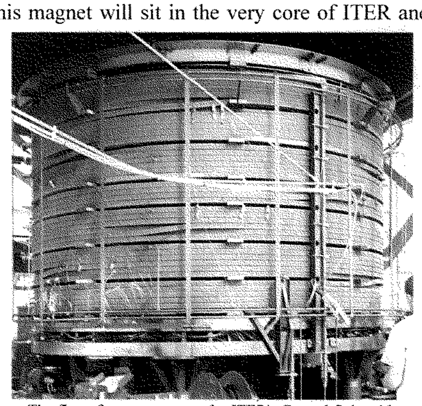
* https://science.energy.gov/~/media/fes/pdf/program-documents/FES_Brochure_hires.pdf
† https://www-pub.iaea.org/books/iaeabooks/Nuclear_Fusion/NF/NFAward

were enabled through a vibrant partnership between national labs, universities, and industry. Separately and collaboratively, these groups have provided pioneering contributions in theory, high-end computing, sensors, magnet technology, and innovative concepts that have advanced our understanding of fusion plasmas and motivated exciting new approaches to achieving fusion energy sooner, rather than later.

This research has enabled the U.S. fusion program to be a world leader in informing the design and research plan of ITER. Looking forward, U.S. leadership in fusion is at risk due to a myriad of challenges including: 1) decreasing U.S. funding at the same time of increased investment in other countries; 2) the increasing scale (and therefore associated investment) of facilities required for fusion development; 3) maintaining university engagement as facilities increase in size and complexity; and 4) the lack of a coherent U.S. strategic plan that defines the technical objectives and associated deliverables for fusion energy development in the U.S. Some recommendations for addressing these issues are discussed later.

General Atomics' role in this enterprise: General Atomics (GA), as a leading industrial partner in the development of fusion energy in the U.S., is committed to the success of the U.S. fusion program and sees compelling opportunities for government-sponsored research to accelerate the path to fusion energy. General Atomics has been involved in fusion energy research for over 60 years. GA presently operates, for the Department of Energy, the largest magnetic fusion User Facility in the U.S. – DIII-D.[‡] DIII-D is a highly collaborative program powered by the contributions of research staff from 28 U.S. universities and 7 national labs as well as GA itself. This program supports over 600 scientific users from 20 countries and has provided numerous pioneering contributions to the technical basis for ITER.

GA is also building the ITER Central Solenoid magnet for the U.S. ITER Project Office as part of the U.S.'s in-kind contributions to ITER. This magnet will sit in the very core of ITER and produce the transformer action that generates 15 million amperes of plasma current in ITER. Because this plasma current is essential for producing the magnetic fields that keep the hot plasma away from the containment walls, the Central Solenoid is sometimes referred to as 'the heartbeat of ITER'.[§] The first of seven production coils – each 14 ft in diameter and 7 ft tall – is now 80% complete with present schedules calling for all seven to be completed by 2022. We hope Members of this Committee will be able to visit our facility in Poway, CA to see the stunning scale of this project and learn more about the ITER project. This broad experience in fusion development provides GA with a unique perspective on fusion activities



The first of seven magnets for ITER's Central Solenoid following heat treatment to create the solenoid's superconducting material.

[‡] https://science.energy.gov/fes/facilities/user-facilities/diii-d/ and https://www.youtube.com/watch?v=tA7J2s23lB8&feature=youtu.be

[§] http://www.newswise.com/doescience/?article_id=639890 within the U.S., both those pertaining to government-sponsored research and investment opportunities for industrial involvement in the fusion enterprise.

U.S. participation in ITER

ITER's mission is to demonstrate the scientific and technological feasibility of fusion energy.[**] This mission is sufficiently ambitious and compelling that seven Members (China, European Union, India, Japan, Korea, Russia, and the U.S.) are partnering together to design, construct, and operate this facility. This consortium represents over 50% of the world's population and over 80% of the world's gross domestic product. The U.S. derives multiple benefits from this partnership including: a) a stronger scientific basis for design and operation of the facility; b) significantly increased breadth of expertise, facilities, and tools; c) industrial fabrication capabilities developed overseas; and d) sharing of costs with the US paying only 9% of the construction cost.

ITER's primary technical goal is to produce plasmas that produce 10 times more fusion power than is being injected into the plasma from external means. The plasmas in ITER will reach 150,000,000 °C, approaching 10 times the temperature of the core of the Sun. At these temperatures, the plasma will enter a state in which the heating from the fusion-produced alpha particles will exceed the heating applied from external sources such that the plasma becomes highly dependent on its own self-organization processes and less on external control (a state known as the 'burning plasma' regime).

The recently released interim report[††] from the National Academies of Sciences, Engineering, and Medicine Committee on a Strategic Plan for U.S. Burning Plasma Research affirmed the importance of research in this regime and of ITER itself stating:

> "*Any strategy to develop magnetic fusion energy requires study of a burning plasma. The only existing project to create a burning plasma at the scale of a power plant is ITER, which is a major component of the U.S. fusion energy program. As an ITER partner, the United States benefits from the long-recognized value of international cooperation to combine the scientific and engineering expertise, industrial capacity, and financial resources necessary for such an inherently large project. A decision by the United States to withdraw from the ITER project as the primary experimental burning plasma component within a balanced long-term strategic plan for fusion energy could isolate U.S. fusion scientists from the international effort and would require the United States to develop a new approach to study a burning plasma.*"

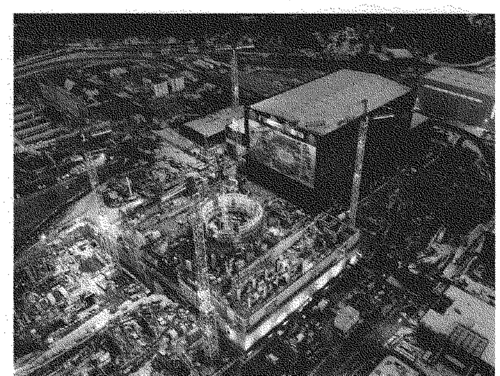
ITER is a highly leveraged investment for the U.S., requiring a 9% of cost investment in return for 100% of the technical information that will be learned from ITER, including the technical know-how developed in the other ITER parties. Over 80% of the U.S. funding is being used to fabricate components and establish technical expertise in the U.S., including the ITER Central Solenoid being built at General Atomics.

Following a management restructuring in 2015, ITER construction has accelerated with delivery

[**] https://www.usiter.org/fusion/U.S._ITER_Factsheet.pdf

[††] National Academies of Sciences, Engineering, and Medicine. 2017. Interim Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research. Washington, DC: The National Academies Press. https://doi.org/10.17226/24971.

of several key components to the ITER site and construction advancing at a rapid pace. The most important action in this restructuring was the naming of a new Director General (Bernard Bigot) who in March of 2015 presented an action plan and was given the authority required to manage this project effectively. This restructuring has resulted in a better-equipped, more nimble organization capable of responding to emerging needs in a timely, effective manner. This is evidenced by the fact that, since 2015, project milestones have consistently been met on or ahead of schedule.[§§] This progress has taken the ITER project past the 50% completion mark for systems that are required for first plasma in 2025. For its part, the U.S. successfully delivered on two major components in FY17: the jacketed superconductors needed for toroidal field coil fabrication and its 75% share of the steady-state electrical network for powering the non-pulsed loads on the ITER site. However, at present funding levels, the U.S. is at risk of falling behind on its deliveries, and its hardware contributions could become the pacing items for ITER assembly.


Aerial view of the ITER site in December 2017

Recommendations for enabling a strong U.S. program in magnetic fusion

The future of fusion research in the U.S. is captured well by three assessments made by the aforementioned NAS Committee in their interim report:

- "*Construction and operation of a burning plasma experiment is a critical, but not sufficient, next step toward the realization of commercial fusion energy. In addition to a burning plasma experiment, further research is needed to improve and fully enable the fusion power system.*"
- "*Recent closures of domestic experimental facilities without new starts, as well as a reduction of fusion technology efforts, threaten the health of the field in the United States.*"
- "*Although our international partners have national strategic plans leading to a fusion energy demonstration device, the United States does not.*"

These three statements convey three important points: 1) U.S. participation in ITER is critical but significantly more R&D remains beyond ITER to realize fusion energy; 2) the U.S. program is suffering due to the lack of new investment; and 3) the U.S. needs a strategic plan that catalyzes research on key enabling areas required in the demonstration of the practicality of fusion energy.

I would like to offer the following recommendations for this Committee in considering the appropriate steps to take to enhance fusion energy development in the U.S.:

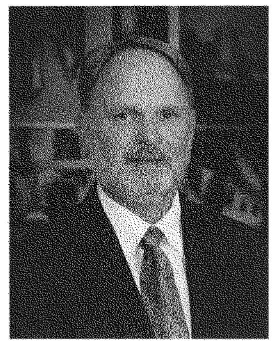
[§§] A set of photographs depicting the achievement of key milestones can be found at https://www.iter.org/album/Media/5%20-%20Site%20milestones

- *The U.S. government should establish a clear, coordinated policy on the importance of fusion energy as a national strategic interest.* At present, such clarity is missing and leads to the inability of the U.S. to plan for a program that moves coherently in any specific direction. As an example, the recent charge to the National Academy of Sciences committee read "The committee may assume that economical fusion energy within the next several decades is a U.S. strategic interest." Yet, funding levels in the U.S. are only sufficient to carry out a modest scientific program and well below levels required for even moderately-paced development of fusion energy.[***] In such a climate, discussions on what/how/when to make new investments are extremely challenging as individuals must lean on their own assessments of the appropriate U.S. policy. Given the potential of fusion as a future energy source, it seems appropriate that the U.S. adopt a policy that includes fusion in its national energy plan. This plan should specify certain energy development milestones that serve to both motivate and direct funding in the development of the science and technology of fusion.
- Consistent with developing fusion as a national strategic interest in the next several decades, *the U.S. should make a firm commitment to fully fund the ITER project.* As noted previously, the scope of the ITER project is far beyond anything the U.S. could achieve on its own. For a highly leveraged investment, ITER will provide U.S. researchers with a research platform of unparalleled capabilities and access to burning plasmas. This is a unique and timely opportunity that we should not pass up.
- *The Office of Science, in concert with the U.S. fusion community, should develop a strategic plan that defines a distinctive pathway for U.S. fusion energy development while at the same time taking advantage of the considerable investment that is being made worldwide.* The fusion endeavor is a grand challenge for the nation and the world. As we move closer to achieving fusion, with larger and more fusion-capable experiments, it will become even more essential to engage the best minds from universities, labs, industry in resolving the key challenges. Therefore, such a plan should include investment in new capabilities either through upgrades or new facilities with the goal of delivering world-class research platforms. This will be essential in attracting, engaging, and maintaining top talent that can work together to provide innovative solutions to key challenges, leadership and support for the success of ITER, and the ability to envision, construct, and operate new larger and more complex facilities.

Thank you for this opportunity to share my views on the future of fusion energy research in the U.S. I look forward to working with the Committee members to develop and implement impactful approaches to ensure that magnetic fusion becomes a major part of the U.S.'s energy future.

[***] https://commons.wikimedia.org/wiki/File:U.S._historical_fusion_budget_vs._1976_ERDA_plan.png

Mickey R. Wade



Dr. Mickey R. Wade is the Director of Advanced Fusion Systems of the Magnetic Fusion Energy Division at General Atomics in San Diego, CA. Prior to serving in this role, Dr. Wade was the Director of the DIII-D National Fusion Program, the largest fusion research program in the US with ~500 researchers from over 90 institutions from around the world. Dr. Wade received his Ph.D. in Nuclear Engineering from the Georgia Institute of Technology in 1991. He is the author of over 30 first-author papers, a Fellow of the American Physical Society, and has served on the Editorial Boards of Nuclear Fusion and Physics of Plasmas.

Dr. Wade has played an active role in the ITER project and fusion development throughout his career. His research and leadership played a significant role in establishing confidence that ITER can successfully achieve and possibly exceed its technical objectives. He worked as part of an international team that developed the ITER Research Plan, which still serves as the primary document for ITER's approach to achieving its technical goals. Subsequently, he served on the ITER Management Advisory Committee, whose role is to advise the ITER Council on management issues of the ITER Project.

In 2017, Dr. Wade was awarded a Chinese Academy of Sciences President's International Fellowship for Visiting Scientists. Over the past year, Dr. Wade has served as a co-chair of the U.S. Magnetic Fusion Research Strategic Directions community workshops, which have provided a forum for U.S. scientists to propose, debate, and identify compelling program elements for the U.S. fusion program.

Chairman WEBER. Thank you, Doctor.
Doctor, is it Herrmann or Herrmann?
Dr. HERRMANN. It's Herrmann.
Chairman WEBER. Okay. You're recognized for five minutes.

TESTIMONY OF DR. MARK HERRMANN, DIRECTOR, NATIONAL IGNITION FACILITY, LAWRENCE LIVERMORE NATIONAL LABORATORY

Dr. HERRMANN. Thank you. Chairman Weber, Congresswoman Lofgren, and Members of the Committee, thank you for the opportunity to appear before this Committee and offer testimony on the future of fusion energy research.

As was already mentioned, I'm the Director of the National Ignition Facility, or NIF, at Lawrence Livermore National Laboratory, which is sponsored by the National Nuclear Security Administration. NIF is a football stadium-sized facility containing the world's most energetic laser. I've had the pleasure of giving NIF tours to several Members of the Committee and of course would be happy to show off the incredible work done by our scientists and engineers to those of you who haven't had a chance to visit.

NIF's lasers are focused on targets smaller than a pencil eraser to create conditions of very high temperatures and pressures called high-energy density or HED. Since greater than 99 percent of the yield of our nuclear weapons comes in the HED state, HED experiments are a critical component of the science-based Stockpile Stewardship Program, which has the goal of ensuring that our nuclear stockpile remains safe, secure, and effective in the absence of further explosive nuclear underground testing.

In addition to NIF, the Z–Pulsed Power Facility, and the OMEGA Laser Facility play complementary roles in the Stockpile Stewardship Program. Experiments on NIF are providing data in important regimes to both enhance and test our simulations of our nuclear weapons. Simulations are incredibly powerful tools, especially now that we're getting better and better computers, but it is essential that they be compared to data in order to avoid getting the wrong answers. NIF, Z, and OMEGA also play a major role in recruiting and training the scientists and engineers who are the next generation of stockpile stewards.

One of stewardship's grand scientific challenges established at the birth of the program is to achieve fusion ignition in the laboratory. Ignition is when the energy released from the fusion reactions further heats the fusion fuel referred to self-heating—referred to as self-heating—leading to more reactions and a large release of energy. Pursuit of ignition provides the United States with an experimental platform to study many incompletely understood aspects of nuclear weapons performance. In contrast to magnetic confinement fusion, inertia confinement fusion is obtained by squeezing the fusion fuel to higher pressures and temperatures than found at the center of the sun.

Early experiments on NIF ending in 2012 fell far short of achieving ignition, despite optimistic projections. A number of experiments were then performed, and many gaps in our understanding were identified. In 2016, NNSA established a goal for 2020 to assess the efficacy of NIF for achieving ignition. Today, we are on track at the halfway point of that goal. In fact, last year, improvements enabled the fusion yield on the best implosions on NIF to date to more than double the previous record yield to over 50 kilojoules. That's 25 times higher than the fusion yields in 2012. These implosions have demonstrated modest self-heating, a critical step on the path to ignition that's akin to trying to light a campfire and having the wood start to smoke.

Simulations suggest that a 30 percent enhancement in either the pressure or the confinement time of this plasma would bring us to ignition, although it is possible to—that the simulations could be wrong, which is why, of course, we do experiments.

We are now pursuing several exciting directions for improving the fusion yield at NIF. If ignition is obtained on NIF, it would be the first time ever in the laboratory, and such a breakthrough could open the path—a possible path to inertial fusion energy, or IFE, that could have significantly different technological risks than magnetic fusion approaches we've been hearing about today. An IFE system would work by using a driver like a laser to ignite targets multiple times per second. To be clear, NNSA does not have an energy mission, and IFE research is not being performed at NIF today.

The National Academy of Sciences studied IFE in 2013, and their report concluded that the appropriate time for the establishment of a national coordinated broad-based IFE program within DOE would be when ignition is achieved. However, the committee also concluded that the potential benefits of energy from ICF also provide a compelling rationale for including IFE R&D as part of the long-term R&D portfolio for the—for U.S. energy. This is an important conclusion of the NAS report.

A number of promising technologies highlighted in the NAS report as key to eventual IFE systems are making steady progress, but without an IFE program, the United States is not in a position to assess the significance of these advances.

A modest IFE investment is all the more justified, given that the United States leads the world in the high-energy density science. NIF, for example, operates with 10 times the energy of the next largest laser in the world, which is in China.

There are few remaining fields of science where the United States currently maintains such a lead over the rest of the world. This world leadership, along with the compelling scientific opportunities such as the grand challenge of ignition, have been a magnet for the best and brightest scientists and engineers to pursue research on the NIF and to join the Stockpile Stewardship Program.

Today, the rest of the world is aggressively catching up. NIF-scale lasers are under construction in both France and Russia, the Chinese are exploring designs for lasers that are 1.5 to 3 times NIF's scale, and in high-intensity lasers the leadership has shifted from the United States where they were invented to Europe and Asia, as noted in a recent NAS study.

While the world is investing more in HED science the fiscal year 2019 President's budget requests reducing funding for the national ICF program by more than 20 percent relative to fiscal year 2017, a reduction of more than $100 million. The proposed budget reduces funding for NIF by more than $60 million, zeroes support for target fabrication at General Atomics, and includes major cuts to the OMEGA Laser Facility, putting the facility on a path to closure over the next three years.

The academic programs that are essential to the field's future are also zeroed. Together, these cuts cripple our academic partners and could lead to the loss of a generation of early-career HED scientists and students. At Livermore, the proposed cuts will lead to a major disruption in our ability to provide the HED experiments needed to support both near-term and long-term stewardship deliverables, and the cuts will strongly impact the pursuit of fusion ignition, leading to a multiyear delay of the goals set out in 2020.

We're close—we are working closely with NNSA and our national partners to manage the impacts of these cuts should they be enacted and remain focused on the highest priority deliverables of the stewardship program, but they must—it must be understood that these cuts will have major negative implications for U.S. leadership in HED science and fusion research.

Thank you again for your time, and I look forward to your questions.

[The prepared statement of Dr. Herrmann follows:]

Written Testimony of Mark Herrmann
Director, National Ignition Facility
Lawrence Livermore National Laboratory

Delivered to the
Committee on Science, Space, and Technology Subcommittee on Energy
United States House of Representatives

Hearing on the Future of Fusion Energy Research
March 6, 2018

Chairman Weber, Ranking Member Veasey, and Members of the Committee, thank you for the opportunity to appear before this committee and to offer testimony on the future of fusion energy research. My name is Mark Herrmann, and I have been the Director of the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) since 2014. Prior to becoming NIF Director, I spent 9 years at the Sandia National Laboratories (SNL) holding a number of positions, including Director of the Pulsed Power Sciences Center that is home to the Z Pulsed Power Facility. I have been involved in inertial confinement fusion research for 20 years, beginning my career at LLNL after completing my thesis research at the Princeton Plasma Physics Laboratory.

With my testimony, I hope to convey several points:

- The NIF, along with the Z Pulsed Power Facility, and the Omega Laser Facility at the University of Rochester, are world-leading scientific capabilities funded by the Inertial Confinement Fusion (ICF) Ignition and High Yield Program of the National Nuclear Security Administration (NNSA) as part of the Stockpile Stewardship Program (SSP). All 3 facilities are providing experimental data and workforce training in the high energy density regimes needed to maintain a safe, secure, and effective U.S. nuclear deterrent without further underground nuclear testing.
- One of the major efforts of the national ICF program and the NIF is to achieve fusion ignition in the laboratory to address a grand challenge established at the beginning of the stewardship program. In 2016, NNSA established a 2020 goal for the ICF program to assess the efficacy of NIF for achieving ignition. LLNL and the ICF community developed a 4-year plan to meet that goal, and we are on track at the halfway point. Recently there has been exciting progress in the performance of NIF implosions resulting in a doubling of the fusion yield.
- If ignition can be achieved, it could pave the way to a broad, national, coordinated plan to pursue Inertial Fusion Energy (IFE), which is an innovative, alternative path that is complementary to mainstream magnetic fusion energy research. Currently IFE is not part of the long-term energy R&D portfolio of the U.S. and is not being researched at LLNL.
- The United States is the acknowledged world leader in the area of high energy density science, thanks to investment by the NNSA and DOE, and broad collaborations are exploiting these capabilities to perform world leading science and develop advanced technology. However, the U.S. lead is rapidly shrinking and there are some subfields of HED research where the U.S. is now behind.
- The FY19 President's Budget Request for the ICF program will lead to major reductions in experiments at NIF and the closure of the Omega Laser Facility, substantially impacting our ability to support the Stockpile Stewardship Program, significantly delaying the pursuit of fusion ignition, and disrupting the pipeline of future HED scientists and stockpile stewards.
- The National Academy of Sciences Committee on a Strategic Plan for U.S. Burning Plasma Research has recently released its interim report, which calls for a long term strategic plan for fusion energy.

The National Ignition Facility is delivering for the Stockpile Stewardship Program

Most of the yield of our thermonuclear weapons is generated in the High Energy Density (HED) state. With the cessation of underground nuclear testing in 1992 and the creation of the Science Based Stockpile Stewardship Program (SSP) in the 1990s, it was recognized that an enduring Stewardship Program would require experimental access to HED regimes to ensure the U.S. nuclear stockpile remains safe, secure, and effective without further underground nuclear testing.

The three major U.S. HED facilities funded by the NNSA are NIF, the Z Pulsed Power Facility at SNL, and the Omega Laser Facility at the University of Rochester. These facilities work together in complementary ways to perform the scientific experiments needed for the SSP.

NIF is a football-stadium-sized facility that houses the world's most energetic laser, (approximately 60 times more energetic than any other laser in the world when it was completed in 2009). NIF's 192 lasers can focus into a target smaller than a dime, creating conditions hotter and denser than those found at the center of the Sun. NIF is being used by stockpile stewards at all three weapons laboratories to obtain critical data in support of the SSP. For example, experiments on NIF are:

- Illuminating key weapons physics issues left unanswered when underground testing stopped, enabling sustainment of the current U.S. nuclear stockpile.
- Providing information that is used to develop and certify the approaches to modernizing our U.S. nuclear weapon systems without additional underground explosive nuclear testing.
- Ensuring the nation is aware of and can assess advances in the nuclear weapons of other nations and avoid technological surprise.
- *Providing experimental data that enables tests of our numerical simulation design codes and is used for the physics models critical to the predictive capability that underpins the science-based SSP.*

Over the last four years we have doubled the rate of experiments on NIF, despite flat funding, helping to reduce oversubscription for this unique capability in the world. Recent accomplishments for the Stewardship Program include:

- LLNL scientists have performed experiments to measure the behavior of plutonium at high pressure for the first time --- previously, only theoretical predictions existed. Experimental data agrees with theory in some regimes and differs from theory in others.
- Los Alamos National Laboratory(LANL) scientists have applied NIF to study the hydrodynamic evolution of sheared flows in never before accessed, relevant regimes. These experiments have led to the development of new models to be consistent with the experimental data.
- SNL scientists have used NIF to study the effects of large x-ray and neutron bursts on test objects to help validate codes that are used to ensure our system's nuclear survivability.

In addition to the experimental data that HED facilities like NIF provide, they also play a major role in recruiting and training the scientists and engineers who are the next generation of stockpile stewards. *In the absence of underground nuclear testing, NIF experiments, particularly ignition experiments discussed below provide an important training ground for our current and future workforce in the skills needed to be successful as stockpile stewards.* This experience is so valuable that, in fact, many of the current leaders of the SSP have participated in various aspects of the national ICF program.

NIF is on track to meet the NNSA milestones laid out for fusion ignition research in 2020

At the beginning of the SSP, a grand challenge goal was set of achieving ignition in the laboratory, to address the most challenging outstanding questions in weapons physics. NIF is the only fully operational facility in the world that is capable of achieving thermonuclear fusion ignition in the laboratory via inertial confinement fusion (ICF). Like magnetic confinement fusion research, ICF research focuses on heating a deuterium-tritium plasma up to the extreme temperatures (>50,000,000K) needed for the fusion reactions to self-heat the plasma, potentially leading to the release of more energy than was invested in the creation of the plasma. Unlike magnetic confinement fusion, which uses a large magnetic field in a large volume to confine the plasma, inertial confinement fusion relies on the inertia of the deuterium and tritium fusion fuel squeezed to incredibly extreme conditions (higher density and pressure than the center of our Sun) to provide the confinement.

Thermonuclear fusion ignition is a process that is critical for our nuclear weapons but is tremendously difficult to achieve with the energy levels available in the laboratory. Pursuit of thermonuclear fusion ignition in the laboratory provides the U.S. with insights into one of the least understood aspects of our modern nuclear weapons by providing experimental data to compare with our modern simulations, giving us critical insights into similar processes taking place in our weapons. In addition, the achievement of this grand scientific challenge, would open entirely new vistas of high energy density science and enable access to regimes even more relevant for stockpile stewardship in the future.

In a NIF ICF experiment, the powerful laser beams are directed into the inside of a hollow cylinder of gold (about the size of a pencil eraser) forming a miniature x-ray oven. Inside the cylinder, the x-rays heat a BB sized plastic capsule that contains the thermonuclear deuterium and tritium fuel, causing it to implode on itself at close to one million miles an hour and shrinking in size from a peppercorn to something 1/10 the size of the period at the end of this sentence. This implosion generates the extreme conditions needed for thermonuclear fusion reactions to take place. Our best simulations using our most powerful computers suggest that given sufficient control over the implosion, fusion ignition will take place and lead to the release of significantly more energy than the laser energy NIF used to create the implosion.

Early experiments ending in 2012 fell far short of achieving fusion ignition, despite optimistic projections from our best simulations at that time. A number of additional experiments were then performed to identify the gaps in our simulation capability. In 2015, NNSA chartered a review of the national ignition effort, and based on that review NNSA released a report in 2016, setting up a principal goal of the ignition effort "by 2020, to determine the efficacy of NIF for achieving ignition and the credible physics scaling to multi-megajoules of fusion yields for each of the major ICF approaches".*

The LLNL ignition program, in partnership with LANL, is now half-way through the plan that was developed in response to NNSA's 2020 goal. As part of that plan - by utilizing clever experiments, advanced diagnostics, and new target designs - we've made a number of significant advances in understanding that have translated into improved implosion performance and higher fusion yield.

In fact, in 2017, changes to the targets used in the experiments enabled the fusion yield in the best implosions on NIF to more than double the previous record, to over 50 kJ, or 25x higher than fusion yields in 2012. The best implosions have demonstrated that the fusion plasma is starting to heat itself, a critical step on the path to ignition and akin to trying to light a campfire and having the wood start to smoke. Current supercomputer simulations suggest that a 30% enhancement in the pressure or the

* NNSA report DOE/NA-0044, *2016 Inertial Confinement Fusion Program Framework*

confinement time of this extreme plasma would bring us to the ignition threshold, although it is important to keep in mind that while these simulations are the best we know how to do - they could be wrong.

Furthermore, there are a number of exciting avenues to pursue as we execute the plan to the 2020 goal. New target designs with bigger and better capsules are opening up larger parameter spaces for experiments, new diagnostics are shedding light on the differences between simulations and experiments, and advances in the science and technology of the NIF laser have opened up pathways to a 40% increase in laser energy, which further broadens the space for ignition.

Ultimately the goal of the ignition effort on NIF is two-fold: to achieve ignition (greater than a megajoule of fusion yield) if it is possible, or to determine with high scientific confidence what is preventing ignition on NIF. In the event that ignition is not attainable on NIF, it is critically important that we understand why, as it is essential for the SSP to be aware of this shortfall in our capabilities. It also prepares us for the possibility of using alternate means to achieve ignition, either by modifying NIF or by developing another ignition capable facility.

Progress on Inertial Confinement Fusion could provide an alternative path to fusion energy

If inertial confinement fusion ignition is obtained on NIF, it would be the first time in the laboratory that a fusion reaction released more energy than was used to generate the reaction. Such a breakthrough could form the basis of a possible path to fusion energy that would have significantly different technological and engineering risks than the concepts being pursued for magnetic fusion energy. To be clear, however, NNSA does not have an energy mission and, therefore, no NNSA resources are being used for IFE research at LLNL.

It is important to acknowledge upfront, like all approaches to fusion energy, that there are a large number of technological, engineering, and scientific challenges to IFE. An IFE system would work by using a driver (such as a laser) to implode an injected target to fusion ignition and yield conditions multiple times per second. There are very significant technical hurdles that would need to be overcome in developing drivers that can operate multiple times per second, in building and injecting ignition quality targets multiple times per second, and in protecting the entire system from the harsh fusion environment associated with large, repeated fusion yields. Furthermore, each of these systems will have to be developed at significantly reduced costs from current levels in order for any energy produced to be economical.

The National Academy of Sciences studied this problem and released an excellent, detailed report in 2013 entitled "An Assessment of the Prospects for Inertial Fusion Energy".[†] A number of conclusions and recommendations were made, including a recommendation to continue progress in target physics research on the various approaches to inertial confinement being pursued on NIF, Z, and Omega facilities. The report was clear in concluding that "The appropriate time for the establishment of a national, coordinated, broad-based inertial fusion energy program within DOE would be when ignition is achieved".[‡] In my opinion a national, coordinated, broad-based IFE program should await fusion ignition.

Nevertheless the committee also concluded: "The potential benefits of energy from inertial confinement fusion (abundant fuel, minimal greenhouse gas emissions, and limited high-level radioactive waste requiring long-term disposal) also provide a compelling rationale for including inertial fusion energy R&D as part of the long-term R&D portfolio for U.S. energy. A portfolio strategy hedges against

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[†] *An Assessment of the Prospects for Inertial Fusion Energy*, Committee on the Prospects for Inertial Confinement Fusion Energy Systems, NRC (National Academies Press, Washington, D.C., 2013).
[‡] Ibid.

uncertainties in the future availability of alternatives such as those that arise from unforeseen circumstances."[§]

The idea that a portfolio strategy should include inertial fusion energy R&D is an important conclusion of the NAS report. *This is particularly true because the DOE is in an excellent position to make rapid progress in this area by leveraging the large investment being made in many emerging technologies and by the NNSA in ICF research.*

As an example of the benefits that would accrue from a small IFE portfolio, a number of promising technologies highlighted in the NAS report as key to eventual IFE systems are making steady progress. In particular, there have been exciting advances in rep-rated laser technology and rep-rated pulsed power technology in the U.S. over the last few years, potentially lowering the cost of a future driver for an IFE system. Additive manufacturing and other automated manufacturing techniques are becoming more cost effective and are being used as part of the current target fabrication effort on NIF. Research in the magnetic fusion community is advancing the potential of liquid metals as first wall materials for fusion reactors, which could also benefit IFE. Unfortunately, without even a minimal IFE program, the U.S. is not in a position to assess the significance of these advances for a potential future IFE system.

The U.S. is the world leader in high energy density science, although that lead is rapidly shrinking

As discussed above, the U.S. investments supported by NNSA and the DOE have made the U.S. the world leader in this area of science, giving the U.S. a competitive advantage and demonstrating to the world our commitment to maintaining a safe, secure, and effective deterrent. As an example, when completed in 2009, NIF operated with 60x more energy than the next biggest laser in the world, which was the Omega Laser Facility, also in the US. Now, nearly a decade later, NIF operates with 10-20x the energy of the next most energetic laser, which is in China. A very similar statement could be made about the Z facility 10 years ago, with the second most energetic pulsed power facility located in the U.S. in 2009 and in China today. There are few fields of science today where the U.S. has had, and currently maintains, such a large lead over the rest of the world. This lead exists not only in facility capabilities but also in diagnostics, targets, simulations, and scientific output and publications. *This world leadership along with the compelling scientific opportunities - especially the grand challenge of inertial confinement fusion ignition and the potential of a path to inertial fusion energy - has been a magnet for the best and brightest scientists and engineers to pursue research in HED science and to work as part of the SSP.*

To ensure healthy engagement with the outside community NNSA, has established cooperative research programs on NIF, Omega, and Z that provide a small fraction of the facility experimental time to academic researchers at other institutions. The proposals are judged on their scientific merit and technical feasibility by external scientific committees and the outside researchers are awarded time on NIF, Omega, and Z to leverage these incredible investments for fundamental scientific studies. For example, academic researchers on NNSA facilities have been studying how the fundamental properties of matter change as the materials are squeezed to higher and higher pressures. These questions are of fundamental scientific interest, are important to understand the structure of planets, and could possibly lead to the discovery of new materials with unique properties and potentially commercial applications.

Such science is also of high interest in the world wide academic community and publications from these cooperative research programs frequently appear in Nature, Science, and Physical Review Letters, and other prestigious journals. This research and these publications are an avenue for NNSA researchers to interact with the outside world, and a very effective advertisement for recruiting students to the Laboratories and into the SSP. *Furthermore, the world-class research that our Lab scientists are*

[§] Ibid.

publishing is one of the most visible manifestations of our deterrent, since the credibility of the deterrent ultimately rests on the quality of the people in the stewardship program. Last but not least, several of these academically-led experiments have developed new and innovative approaches to HED science that have then been adopted for use in addressing core SSP questions.

The world leading nature of NNSA's ICF facilities requires cutting edge science and technology, that in turn leads to many spinoff benefits. For example, NIF requires unique capabilities in lasers, optics, precision target fabrication, diagnostics, and computer controls. Developments in these areas have led to a large number of R&D 100 awards over the years and a proliferation of ideas that support our national security (e.g. direct energy weapons) and our economic competitiveness (e.g. Extreme Ultraviolet Lithography).

While historically we have had an impressive lead in HED science, it is clear today that the rest of the world is aggressively focusing on catching up. Currently, megajoule (NIF) scale lasers are under construction in both France and Russia. The Chinese have completed and are operating the second most energetic laser in the world and are publishing papers with designs for lasers 50% to three times the size of NIF (note that having more energy makes achieving inertial confinement fusion ignition easier).

The area of high intensity lasers is a particularly noteworthy example. Researchers in the U.S. pioneered the field of high intensity lasers. These lasers reach more extreme conditions not by increasing the energy delivered, but by reducing the duration of the laser pulse, achieving higher and higher powers as the duration is reduced. In the 1990's, LLNL broke the petawatt (10^15 watts) barrier with the construction of the Nova Petawatt. A number of novel and important new properties emerged at the high intensities that these new lasers enabled, and since then dozens of petawatt class lasers have been built and thousands of publications on the exciting science in this area were published over the next 20 years. In December, the National Academy of Sciences published a report on "Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light". A key conclusion from this report is that the:

> "The U.S. has lost its previous dominance. The United States was the leading innovator and dominant user of high-intensity laser technology when it was developed in the 1990s, but Europe and Asia have now grown to dominate this sector through coordinated national and regional research and infrastructure programs. In Europe, this has stimulated the emergence of the Extreme Light Infrastructure (ELI) program. At present, 80 to 90 percent of the high-intensity laser systems are overseas, and all of the highest power (multi-petawatt) research lasers currently in construction or already built are overseas".[**]

The FY19 President's Budget Request (PBR) for the Inertial Confinement Fusion Program will significantly delay pursuit of fusion ignition as a goal for the SSP, make significant cuts to the National Ignition Facility, and lead to the closure of the Omega Laser Facility.

NNSA's FY19 PBR reduces funding for the national ICF program by more than 20% relative to FY17, a reduction of more than $100M nationally, and reduces funding for the ICF Program at LLNL by $59M-$73M (depending on final FY18 funding level and including effects of cost shift for target fabrication). The budget request also includes drastic cuts to the Laboratory for Laser Energetics at the University of Rochester, an essential partner for LLNL, NIF, and the national ICF program. In particular, the request for LLE is $45M, a reduction of $28M-35M (depending on final FY18 funding level and including cost shift for target fabrication). The budget document states that the Omega Laser Facility will be closed over the next three years. The target fabrication budget for General Atomics and Schafer, which have been

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[**] *Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light*, Committee on Opportunities in the Science, Applications, and Technology of Intense Ultrafast Lasers; NAS (National Academies Press, Washington, D.C., 2017).

strong partners in enabling many of the advances of the national ICF program for decades, has been zeroed. Finally, the academic programs that are key to the field's future are reduced from $9.5M to zero. Coupled with the reductions at the Omega Laser Facility, where many academics and their students perform their research, these cuts cripple our academic partners and could lead to the loss of a generation of graduate students doing research in the field of HED science and discourage students and early career scientists from pursuing careers in this area of HED science.

LLNL is working closely with NNSA and our national partners in the ICF Program to minimize the impact of these cuts should they be enacted and to remain focused on the highest priority deliverables for the SSP. A detailed implementation plan has not yet been developed, but it is our assessment that reductions in funding of this magnitude to the ICF Program will lead to major disruption and reduction in our ability to provide the data needed in support of both near- and long-term SSP deliverables. *We also assess that the cuts will significantly delay the pursuit of fusion ignition and yield on the NIF, and means we will not meet the NNSA goal set out for 2020.* At LLNL, the proposed budget eliminates funding for nearly half of the scientists and engineers working on the ignition effort, representing a significant portion of the U.S. expertise in this area. Since almost every HED experiment supporting SSP has arisen from tools or capabilities initially developed to address the grand scientific challenge of ignition, these cuts will affect the long-term prospects for providing the data needed for the Stewardship program, and negatively affect recruitment and retention of stockpile stewards.

The proposed cuts at LLNL, coupled with the reduction at other sites, will impact every aspect of the operations of NIF. They will lead to a reduction in operating hours and experiments performed (>30%) as resources are shifted to maintain critical skills and fill needed capabilities lost by reductions to partner institutions. The reduction in experiments performed will impact all users of NIF, reducing opportunities for stockpile stewards, greatly reducing ignition research, and reducing opportunities for the academic community and users pursuing other important national security applications on NIF. NIF will also need to significantly reduce its peak laser power and energy, affecting the fidelity of many experiments. Unique experimental capabilities that have been developed for addressing challenging weapons physics issues will need to be placed in cold standby. As such, these proposed reductions will lead a degradation of NIF's capabilities over time. The cuts to the University of Rochester Laboratory for Laser Energetics will eliminate the efficient development of new experimental platforms on Omega that are eventually fielded on NIF, significantly increasing the time it takes to develop platforms needed for weapons physics.

Obviously, if these cuts were to be enacted it would be devastating to our field with impacts beginning today and persisting well into the future. When viewed through the lens of developments around the world, these reductions would slow the U.S. down significantly at a time when the rest of the world is accelerating.

The National Academy of Sciences Committee on a Strategic Plan for U.S. Burning Plasma Research has recently released its interim report.

While the focus of my own research for the last 20 years has been on inertial confinement fusion, I have remained an interested observer in all aspects of fusion energy research. Currently, I am serving on the National Academy of Sciences Committee on a Strategic Plan for U.S. Burning Plasma Research which is focused on magnetic fusion energy research. Our committee, Co-Chaired by Professor Michael Mauel, Columbia University, and Professor Mel Shochet, University of Chicago, has recently released its interim report and is working now on the final report.

A brief summary of the main assessments from our interim report follows[††]:

Any fusion strategy requires a burning plasma experiment.
If the U.S. wishes to maintain leadership in this field, it needs to develop its own long-term strategic plan for fusion energy.

Major Assessment:

- The only existing project to create a burning plasma at the scale of a power plant is ITER, which is a major component of the U.S. fusion energy program.
- As an ITER partner, the United States benefits from international cooperation to combine the scientific and engineering expertise, industrial capacity, and financial resources.
- A decision by the United States to withdraw from the ITER project could isolate U.S. fusion scientists from the international effort and would require the United States to develop a new approach to study a burning plasma.

Why is Burning Plasma Research Important?

Burning plasma research is essential to the development of magnetic fusion energy and contributes to advancements in plasma science, materials science, and the nation's industrial capacity to deliver high-technology components. All efforts to make fusion energy require a burning plasma—an ionized gas like the Sun and stars that is heated by fusion reactions. Although significant fusion power has been created in the laboratory, a burning plasma, which is heated predominately by fusion reactions, has never been created.

In addition to a burning plasma experiment, further research is needed to improve and fully enable the fusion power system.

Status of U.S. Burning Plasma Research:

- The U.S. fusion energy science program has made leading advances in burning plasma science that have substantially improved our confidence that a burning plasma experiment such as ITER will succeed in achieving its scientific mission.
- Recent closures of domestic experimental facilities without new starts, as well as a reduction of fusion technology efforts, threaten the health of the field in the United States.
- Although our international partners have national strategic plans leading to a fusion energy demonstration device, the United States does not.

If the United States wishes to maintain scientific and technical leadership in this field, the committee concludes that the United States needs to develop its own long-term strategic plan for fusion energy. In the development of the final report, the committee views the following elements as important to its guidance on a long-term strategic plan:

- Continued progress towards the construction and operation of a burning plasma experiment leading to the study of burning plasma,
- Research beyond what is done in a burning plasma experiment to improve and fully enable commercial fusion power,
- Innovation in fusion science and technology targeted to improve the fusion power system as a commercial energy source, and
- A mission for fusion energy research that engages the participation of universities, national laboratories, and industry in the realization of commercial fusion power for the nation.

[††] *Interim Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research.* (National Academies Press, Washington, D.C., 2017)

Mark Herrmann

Dr. Mark Herrmann is the director of the National Ignition Facility (NIF), the world's largest laser and a key experimental facility for the National Nuclear Security Administration's science-based Stockpile Stewardship Program (SSP) located at Lawrence Livermore National Laboratory. In this role Mark has leadership and management responsibility for the NIF and the 650 person team that operates, maintains, and develops its new strategic capabilities. Dr. Herrmann works closely with the leaders of the Stewardship program and the national Inertial Confinement Fusion and Experimental Science programs, as well as the National Security Applications and Discovery Science communities, to ensure NIF is delivering for the Stockpile Stewardship Program.

Mark returned to LLNL to become the NIF Director in October 2014 after 9 years at Sandia National Laboratories, where he led research on the use of large magnetic fields generated by the Z facility to create and control high energy density matter. While at Sandia, Dr. Herrmann held a series of staff and management positions, including Director of the Pulsed Power Sciences Center. Prior to joining Sandia in 2005, Mark was a physicist at LLNL, where his research focused on Inertial Confinement Fusion and high energy density science. Dr. Herrmann was awarded a Presidential Early Career Award for Scientists and Engineers, the American Physical Society Award for Outstanding Doctoral Dissertation in Plasma Physics, three NNSA Defense Programs Awards of Excellence, and the Fusion Power Associates Excellence in Fusion Engineering Award. Mark is a fellow of the American Physical Society. He received his undergraduate degrees from Washington University in St. Louis, and his Ph.D. from the Program in Plasma Physics at Princeton University.

Chairman WEBER. Thank you, Doctor.

I now recognize myself for five minutes.

Dr. Bigot, in your testimony you stress that ITER is an integrated project whose success relies on the performance of each of its constituent members. Be as specific as you can. Could you explain what would happen to the ITER project if the United States fails to meet our commitments to the ITER project?

Dr. BIGOT. Thank you very much. It's very clear that the United States has two roles, even three I would say. The first one is to provide in-kind components, and you understand maybe that this tokamak facility is a highly integrated facility in such a way that if a component is not onsite and under specification, on time, it will stop the whole project.

The most important equipment which is to come soon is the central solenoid that we spoke about. It is the backbone I would say of the whole facility. As well there is the tokamak cooling water system is a system that will extract the heat from the tokamak. There are also several diagnostics, which are absolutely needed. You will see that indeed in 2018, 2019, 2020, most of the components have to be completed and to be delivered. If some of the component is not properly designed on time, it will impact everything.

The second point is the ITER Organization. Beyond the responsibility of the United States, ITER Domestic Agency, National Oak Ridge Laboratory, the ITER Organization has a responsibility to install and assemble all these components coming from all over as well. In 2018, early 2019, I have to place all the nine assembly contracts with some leading companies in such a way that between 2018 and 2024, six years, we will be able to assemble these components.

So if the United States doesn't provide the in-cash contribution, we will be behind budget. Right now, the United States has not paid the in-cash contribution in 2016, 2017. It's something around 70 million of euro owed, and for 2018, we have low expectation if we stay with the 63, so it's very important that we keep in.

Chairman WEBER. Thank you. My time is getting away from us a little bit. I appreciate that insight.

Dr. Van Dam, let me come to you. Will the Department of Energy commit to honoring our obligations under the ITER agreement? What say you?

Dr. VAN DAM. Well, I'm speaking on behalf of the Administration. As you know, the Administration is doing a review of all civil nuclear-energy-related activities. ITER has been included in that, and we are waiting for that to provide a decision about whether the United States stays in ITER or not. In the meantime, funding is provided for the two highest hardware systems that we're providing. One was just mentioned, the central solenoid at General Atomics. The other is the tokamak cooling water system also mentioned.

Chairman WEBER. Of course I served in the Texas Legislature with Governor Perry for four years. Do you know, is the Secretary aware of this project or how aware is he maybe I should ask you?

Dr. VAN DAM. That may be beyond my pay grade, but I certainly hope he is. I know he's had letters from people like Dr. Bigot and others, and they've been given to us to write responses——

Chairman WEBER. Okay.

Dr. VAN DAM. —and there is a visit coming up from state heads.

Chairman WEBER. If I give you his cell phone, will you call him? Just——

Dr. VAN DAM. I remember him fondly from Texas.

Chairman WEBER. Dr. Van Dam——

Mr. FOSTER. Would the Chairman yield for a moment on that? I can speak from personal experience.

Chairman WEBER. Yes, sir. You bet.

Mr. FOSTER. Yes, no, the Secretary is actually very plugged into it and very, very enthusiastic about this. He really, you know, sees his role as an advocate for the entire program of which—of fusion. I spent a day with him as he visited the two labs near my district, and so the answer is unquestionably yes.

Chairman WEBER. Well, absolutely good to know. I appreciate the gentleman.

Dr. Van Dam, next question. What type of research in advanced scientific computing and materials science do you think should be prioritized in order to support the Fusion Energy Science program in the next few years?

Dr. VAN DAM. Yes. As you know, advanced computing is a priority of the Administration I think across the government, and for Fusion Energy Science we are looking to advances in exascale computing, which would really help us a lot. We have very, very big codes that we run and have been running for decades.

Another area is data science, which includes machine learning, and we think there's a strong potential for quantum information science to help our field, especially in applications. Now, was that the entirety of the question or was there——

Chairman WEBER. Yes, and I need to move on. I'm running out of time here if I may, so thank you for that answer. This is a question for all of you, so we'll start with Dr. Bigot.

Dr. Bigot, have you thought about or what impact do you think the commercialization of fusion energy could have on climate change?

Dr. BIGOT. Really, as you know, many have found, okay, plasma and the burning plasma will deliver an energy without any impact on the climate. We just release helium if we release anything, and it is benign, chemically benign, no impact on the climate, no impact on the environment. So it's one of the most important advantages we could expect from this technology.

Chairman WEBER. Okay. Dr. Van Dam, same question.

Dr. VAN DAM. Yes, I would echo that answer and just say that if you look at certain Asian countries, for example, that have great problems with pollution and so forth, they are pursuing fusion very vigorously.

Chairman WEBER. Right. And offline at some point I'd be interested in a discussion about the amount of energy that goes into the solenoid, the electromagnetic coil, how you get there, what produces that energy, and what it costs, but we'll do that at a later date.

Dr. Wade?

Dr. WADE. Yes, I would just echo the same answer. I will point out that fusion has the potential to be a large baseload source of electricity, which renewables, without battery storage, have a challenge doing that. So creating a carbon-free footprint with a large baseload will sort of transform how fusion is—and how energy is produced in this world so——

Chairman WEBER. Okay. Dr. Herrmann?

Dr. HERRMANN. Just echoing my other fellow members here—committee—the fusion is a game-changer for the future energy sources of this planet, so it is—it takes a lot of work. It's very hard to achieve fusion, but I think it's definitely worth the investment that's been made.

Chairman WEBER. I thank you. I now recognize the gentlelady from California.

Ms. LOFGREN. Thank you, Mr. Chairman.

You know, I was thinking about all of the great work that each one of our witnesses is doing, and I was thinking about the—specifically, the National Ignition Facility, which I've been interested in since its inception. I think I was there at the groundbreaking in '97, and certainly when we—there were some glitches in the construction, but ultimately at the opening—I remember I spoke at the opening. There was tremendous optimism at the time that ignition would be achieved in a very short time frame, and I remember saying all that will be left will be the engineering and people laughing.

But here we are. It's a slog. It's a slog, and yet the stakes are very high for humanity and our future not only in terms of zero-emission energy but potentially even for remediation of damage that has already been done. So this is an investment that I think is essential for our future.

In your testimony, Dr. Herrmann, you referenced the 2013 National Academy report that basically says the potential benefits of energy from inertial confinement fusion provide a compelling rationale for including inertial fusion energy R&D as part of the long-term R&D portfolio for U.S. energy. However, that followed their other statement, which basically said the appropriate time to establish national coordinated broad-based inertial fusion energy program within DOE would be after ignition is achieved. So if you don't make the investment, you'll never get ignition. Can you help us understand these two apparently conflicting comments?

Dr. HERRMANN. Well, I guess I see it as—that they can be complementary in this way when ignition is achieved—and I think it's a when, not an if—it will be, you know, a potential different path with different risks compared to magnetic fusion, so it's an attractive option that mitigates risk in this high—this very technically risky endeavor. At that time it would be appropriate to have a very broad-based approach, which would mean we're looking at the drivers, the targets, the chambers, everything that needs to be put together to develop an energy source.

Until that time, though, it seems to me that it would be—would be in a better position if we were doing a small level of investment, a modest program that is looking at technology development because technology is moving forward, and then the United States would be in a position to really assess what are the impacts of these advances and be in a better position when ignition eventually happens.

Ms. LOFGREN. Well, and I'd just like to note, I mean, 25 years ago when I first started meeting with fusion scientists, I came into the understanding that there are divisions, you know, magnetic and it's almost a religious belief. I don't share those conflicts. Whatever works, I'm for all the science, and I think as time has gone on, the scientists have gotten to that position as well.

I understand—you know, actually in 2016, working with Secretary Moniz, I asked him to put together an assessment of the current status of federal support for inertial fusion energy and potential action items. He did with the career professionals in the Department. Now, we've had some personnel changes at DOE, but the career professionals are still there, and it's my understanding that really this is not a partisan issue. It never has been and hopefully never will be.

So, Dr. Van Dam, do you agree with the recommendations of the National Academies report that has been referenced in terms of the development of inertial fusion for energy applications, that they're still worth addressing? Do you think we should find a way for strong merit reviewed proposal for inertial fusion energy research?

Dr. VAN DAM. Thank you. And let me begin by saying thank you so much for your passionate interest in fusion energy, be it magnetic or inertial or both. The Administration follows the recommendation from the National Academy report that the appropriate time for the establishment of a coordinated program in inertial fusion energy would be when ignition is achieved, and so at the present time it does not support large-scale investment by the Office of Science at the present time. I'm sure that Dr. Herrmann's efforts will bring that to pass soon.

And our investments in FES are then appropriately limited as well. We do invest specifically in IFE technology through the SBIR program for drivers and diagnostics. At the same time, we are supporting the science that underlies IFE——

Ms. LOFGREN. Right.

Dr. VAN DAM. —and HEDLP.

Ms. LOFGREN. Let me ask you, Dr. Herrmann, I was stunned by your testimony that a 30 percent enhancement the models show us we get to ignition. Now, you've made tremendous changes in performance of the NIF in your tenure as Director since 2014. Is that enough to—if—absent significant reductions in support, can you envision getting that 30 percent? Can you tell us where you're going to be or your best estimate with even support?

Dr. HERRMANN. I frequently say you have to be an optimist to work in fusion.

Ms. LOFGREN. Or to be in Congress.

Dr. HERRMANN. We have, you know, very sophisticated simulations that guide us in the work we're doing. We find—and when we do experiments—and we've been developing better diagnostics—that there are gaps between what our simulations say and what we observe. If we can close those gaps, then the simulations suggest that we should be able to get over the threshold and get to ignition. And we see promising paths forward. So we're making progress, and that's the reason for my optimism. But we don't know until we get there——

Ms. LOFGREN. Of course not.

Dr. HERRMANN. —if we'll be able to get there or not. I feel like we've gone a big part of the way to where we need to get to, and so that's—and I think there's a large parameter space and an incredibly dedicated team of brilliant scientists and engineers working on it, so I think if we have the wherewithal to continue, we will eventually get there, but I don't know.

Ms. LOFGREN. I think my time is expired. I yield back, Mr. Chairman.

Chairman WEBER. I thank the gentlelady.

The gentleman from California, Mr. Rohrabacher, is recognized for five minutes.

Mr. ROHRABACHER. Thank you very much.

Dr. Van Dam, how much money has been spent on trying to produce fusion energy so far?

Dr. VAN DAM. My goodness. By the United States or by—

Mr. ROHRABACHER. No, everybody, but United States and then everybody.

Dr. VAN DAM. I would have to take that on as a homework assignment.

Mr. ROHRABACHER. You don't know?

Dr. VAN DAM. Well, are you talking about integrated over the past—

Mr. ROHRABACHER. Well, we're talking about a major project here. You don't know how much money has been expended so far by the people who are engaged in this coalition to create fusion energy?

Dr. VAN DAM. Are you speaking of ITER?

Mr. ROHRABACHER. I'm not. I'm talking about fusion energy now.

Dr. VAN DAM. We have a current fiscal year 2019 budget request of $340 million.

Mr. ROHRABACHER. We do, right.

Dr. VAN DAM. Yes.

Mr. ROHRABACHER. And——

Dr. VAN DAM. To the Congress, and then it's up to you of course.

Mr. ROHRABACHER. Okay.

Dr. VAN DAM. The fiscal year 2017 enacted was $380 million. Before that it was a bit higher. It was running about $400 million per year.

Mr. ROHRABACHER. Okay. So you know the budget for the last two or three years but before that—have we spent billions of dollars on fusion energy over the years and with our allies——

Dr. VAN DAM. Yes.

Mr. ROHRABACHER. —billions and billions? How much—have we had any actual realization at all of something other than the computer models that suggest that we're going to get there, if we had an ignition of fusion—manmade fusion energy?

Dr. VAN DAM. Well, there are two examples, one in the United States, one in Europe. The U.S. example was the TFTR tokamak at Princeton. This was the late '90s, and they got very close to breakeven. The Joint European Torus likewise around the same time got even—

Mr. ROHRABACHER. Very close isn't the——

Dr. VAN DAM. Yes.

Mr. ROHRABACHER. —is not yet, right?

Dr. VAN DAM. Well, those were still smaller machines.

Mr. ROHRABACHER. Yes. But very close didn't—doesn't work.

Dr. VAN DAM. Well, there's breakeven and then there's—

Mr. ROHRABACHER. Well, we have manmade fusion energy. Do you have something that went on for a minute worth of fusion energy? No.

Dr. VAN DAM. Well, national security applications, but they don't last that long.

Mr. ROHRABACHER. I mean—okay. Well, let us note that we've had very little physical evidence that is actually happening. We've got a lot of computer models here, and let me just note that I have seen—I've been here for a while. I actually—a lot of computer models that didn't work, and is it possible that we will get to the end of this project and it won't work?

Dr. VAN DAM. I sincerely hope not, and the best—

Mr. ROHRABACHER. That's not—no, no, no, is it possible that it won't work?

Dr. VAN DAM. The best projections from experiments that we have done over the past decades and our experience, the database, the computer modeling, and the new technology that we have, we think it will definitely work.

Mr. ROHRABACHER. We think, we think, we think. Okay. Let me just note this, that I would love to believe in the dream of fusion energy. I'd love to believe that. And it's very—and it's possible from what I've heard people say. It's possible we will get there. But we know that with the expenditure of the kind of money that we've spent on fusion energy, we could have developed fission energy alternatives that are for sure not just computer models but are for sure. And we have nobody—when you're interviewed about those model saying well, I think—no, they are very sure General Atomics, for example, has come up with a number of alternatives that they know they can complete.

And I would suggest that with the limited amount of money that we have that we should be going for those things that we know we can actually do when it comes to the nuclear production—nuclear energy production of electricity. And this project has been going a number of years. We're spending billions of dollars, and we still do not know for sure whether or not there will be the type of ignition that we keep spending money on.

Let me just note that we do have byproducts that I—let me tip my hat to General Atomics and others involved in this project. Mr. Chairman, there are byproducts that we have had from this research that have permitted the development of new materials and things such as that that may in the end turn out to be worth the investment without fusion. But in terms of actually producing energy, I think the American people deserve us to go for a for-sure outcome of electricity that we could spend the same amount of money on rather than something that could work because the computer models tell us so.

And, Dr. Bigot, go right ahead. I know you're anxious to refute that or say something good about it. Please use my time to do that.

Dr. BIGOT. If I may just a second—

Mr. ROHRABACHER. Yes.

Dr. BIGOT. —from my point of view we have achieved what the computing modeling has been able to achieve, which means the JET we knew, it could not deliver more than 70 percent of the fusion power it received.

Chairman WEBER. Was that 70 or 17?

Dr. BIGOT. Seventy, seventy, 7–0, you see? Because of the size, is it not possible to have a net fusion power, but we had fusion power but not in the outcome. It's why with ITER we need a larger tokamak. We need a larger vacuum vessel. And the expectation is to have 10 times the fusion power that we will feed in with the heating system, 500 megawatt of fusion power.

So everybody in this audience has to understand there is a minimum size. If you want to get, okay, fusion power, you need to have sufficient number of fusion event per unit time in order to deliver. So my understanding is, so far, the computer modeling has done very well and is why from my point of view I am confident that if we are able to assemble properly all the components making this ITER facility, we will deliver.

Mr. ROHRABACHER. Thank you very much.

Thank you, Mr. Chairman.

Chairman WEBER. Now, if that hadn't confused you, Congressman, he can keep talking.

Mr. ROHRABACHER. Yes.

Chairman WEBER. I think what he's saying is that we're making progress, and so I'm glad that he's here and explaining it to us.

The gentleman yields back. I appreciate that.

Mr. McNerney, you're recognized for five minutes.

Mr. MCNERNEY. Well, I thank the Chairman. I thank the panel. I have to say I've been an enthusiast for fusion energy since college, since graduate school. I worked with Los Alamos labs at the time on inertial fusion. But we have a lot of progress, and I really truly believe that humanity is going to depend on fusion power for the long run. I mean, I don't see any other energy source that's going to really supply our human race with enough energy in the long-term future than fusion. So I'm going to continue to support the progress.

Dr. Van Dam, you said that the United States is the leader in the computer modeling of fusion. What gives us the ability to be the leader? Is it the computer power that we have or is it the computer scientists? What is it that gives us that leadership?

Dr. VAN DAM. Yes, a couple of things. We have very advanced leadership class computing facilities: Oak Ridge and Argonne. We have a national energy research computer center out in California, which, when it started, actually was a magnetic fusion energy computer center and then it broadened into the entire Office of Science. We have the SciDAC, the Scientific Discovery through Computing program, which brings together the subject matter experts in physics and science with applied mathematicians and computer scientists. And this is very powerful. I've seen results of computer simulations gone from half the time required to do them just because the mathematicians and C.S. people have been involved.

Mr. MCNERNEY. So is our leadership being challenged by the supercomputers that they're building in China now or other—or is it just the major infrastructure that we have that allows us to maintain that leadership?

Dr. VAN DAM. Other countries do have very powerful computers. You mentioned China. We are trying to make up for it with intelligence and the way we use them, but yes, we do need to move on. Exascale is a very big priority in the Administration, and even after that, quantum information science.

Mr. MCNERNEY. Okay, thank you. Dr. Wade, you mentioned that there needs to be a comprehensive plan for fusion. Is there an outline for such a plan that we can consider or are we—I mean, as my colleague Bill Foster said, it's like fractal. The closer you look at it, the more sort of different approaches there are. How can we get our hands around this thing?

Dr. WADE. Well, first off, let me just say that when I speak of comprehensive strategic plan, I'm talking about getting to fusion development, fusion energy, not just the next steps in what fusion energy is——

Mr. MCNERNEY. Right.

Dr. WADE. —and so we have to have a goal and we have to have an objective for the United States of what that is, on what time frame, so I think we need to establish that.

I think there are—is the framework of a strategic plan that has been encouraged through processes that the Fusion Energy Sciences division has organized through their advisory committee, but that look more closely at the near term than the long term, and I think we need to try to understand where we want to go in the long term to do that. So, for example, right now we're focused a lot on plasma physics, on—a lot on confinement.

To ultimately deliver fusion, you have to get into materials, you have to get into technology for fuel, tritium fuel cycle handling, things like that. These are technologies that are not just off-the-shelf things. They're not going to be developed in another area. They have to be developed within the fusion context. And so these are things we should be looking at and trying to figure out where we need to go to be the leaders in that.

So I think there's a framework in place to start from the plasma physics side and the burning plasmas that will get an ITER but we also need to fold into that what technologies we need to develop in the future and start that work now rather than later because if we start later, we're just going to make this a serial process that takes for a—a very long time to do.

Mr. MCNERNEY. Okay. Well, we're going to depend on you to point us in the direction of a plan so that we can at least get our hands around that.

Dr. WADE. Yes.

Mr. MCNERNEY. Dr. Herrmann, welcome to my little section of the world here today. I appreciate—I've been to your facility many times. I appreciate what all is involved, and I understand that your real mission is the stockpile maintenance and so on, but you have such a world-class facility. How can we more expand that facility to use in terms of developing fusion power? I know that NNSA is very protective of your facility. How can we expand that a little bit?

Dr. HERRMANN. Thanks for the question. So going back to the very original documents that—the key decisions that led to the creation of the NIF, it was recognized that inertial fusion energy was one possible application. This was all when the Department was the Department of Energy before NNSA was created. And in those documents it says that some fraction of the time on the facility would be open to the scientific community, and so we do open up about eight percent of NIF's time to the outside academic community. And that has allowed us to do world-leading science and attract future stockpile stewards and collaborate with scientists, great scientists at academic institutions around the United States.

Because there currently isn't really a funding path for researchers who want to do IFE, we don't really get proposals in the area of IFE into that open call for time on NIF, and so I think it's kind of a chicken-and-egg thing. It's hard to get the researchers to put in proposals because they don't have a path to get research funding, so if there was such a path, I think that would be a way that some of that time could be used for fusion energy research.

Mr. MCNERNEY. Thank you again. I thank the panelists. I'm going to have some questions for the record since I'm out of time here. I'll submit those later.

Chairman WEBER. I thank the gentleman from California. The gentleman from Oklahoma is now recognized.

Mr. LUCAS. Thank you, Mr. Chairman. And thank you to the panel for being here today. We have kind of drifted from the specifics to the general and back and forth in this conversation, so first let me turn to Dr. Bigot. Those are most impressive pictures compared to the last time several Members of the Committee were onsite at ITER, the progress that's been made. You said in your written testimony—you used the phrase in referencing ITER's magnitude and complexity, quote, "No country, not even the most advanced, could have done this alone," unquote. Could you expand for a moment on the magnitude of the overall cost projected for the whole project and the number of disciplines and the number of engineering and scientific people required to get to this point?

Dr. BIGOT. Thank you very much for this question. Yes, clearly, with tokamak, which is the largest we have ever conceived to build in the world, is utilizing many technologies. First, clearly the magnets, we have to develop the superconducting materials, nearly 2,800 tons of this material has to be developed and with high standards. Vacuum; we need to make a vacuum in a chamber which is nearly 1,000 cubic meters, and we will deal with hydrogen, as you know, which fuels a lot, so we need to develop some specific pumps for that. And the United States is performing quite well in this matter. It is another matter we will need to have the United States delivering on time. There are also heat exchanging requirements. We are producing 500 megawatts, and in a per square meter, we will be able to collect 20 megawatts per square meter.

So all these technologies are so large and the size of the material is so important that we don't believe a single country could develop an industry in order to deliver on a reasonable time. We will deliver nearly the full construction in 25 years, and we have the seven largest countries in the world together, and so you could imagine that even a single one could take maybe four or five times longer, so it would not be expected.

Just to give you an example, one sector of the large vacuums, which is manufactured right now in Korea, it takes four years for the most advanced companies in the world in order to be able to manufacture these sectors. Why? Because we need a very high precision. We need also full alignment because it's a nuclear vessel, so no leaks at all. Every welding has to be precisely controlled.

So my understanding is very clear. If we are not working all together, bringing the added value of our expertise and competence worldwide, it will be very challenging to do it.

Mr. LUCAS. Thank you, Doctor.

Dr. Van Dam, various comments have been made about the different theoretics and the different perspectives, the different ways of coming about trying to address fusion. Could you touch for a moment on what varieties of fusion research programs are being pursued in other countries? We've listened to discussions about the United States. We know what ITER—the consortium we're a part of, but what's the rest of the world up to?

Dr. VAN DAM. Yes. The United States I think is a world leader.

Mr. LUCAS. Absolutely.

Dr. VAN DAM. No doubt about that. The Europeans have a very vigorous program in fusion energy and have had for some time, and we collaborate with them, for example, on the Joint European Torus, which is in the U.K. and it's being impacted by Brexit. We work on the W7–X stellarator, which is the world's largest in Germany. We work on the tokamak in Germany—another tokamak in Germany. We work with all of the countries in collaboration.

Japan has a very vigorous program, and I myself have been going there for almost 40 years to do research. China has a very strong program right now. They're spending a lot of money in fusion energy. They're very serious about it, South Korea as well, India likewise. The Russian Federation used to historically have a very strong program, and we competed with them, and it is still strong. They have a lot of legacy work, but a lot of those scientists have migrated to the United States.

Mr. LUCAS. One last question, Dr. Van Dam, whether you are the optimist and you believe when the technology breakthrough comes or you're a pessimist and you believe if the technology breakthrough comes, describe to us where will the United States be if we don't participate, if we're not a part of these efforts, if we're not doing the research? Where will we be if or when—I would hope when this happens—describe for us just a moment what the world would be like for those who are not a part of this energy source?

Dr. VAN DAM. The ITER project?

Mr. LUCAS. ITER or the concepts of fusion in general. If we get to the point where we have successful fusion power generation but we've not participated, we're not a part of any of the endeavors, we've decided we don't want to spend any money, describe for a moment what it will be like to be left out of the next generation of energy.

Dr. VAN DAM. Well, fusion and also fission provide baseload energy, which is something that renewables don't quite provide and they're also load-following types of energy, which is very important for large industry and just our standard of living. If we are not in the ITER project, it may still go forward with the other six members. You know, we would have to decide what our program—we still have the same priorities in terms of burning plasma science but how they would be implemented. And for the rest of the answer, I would like a crystal ball.

Mr. LUCAS. Bottom line is of course if success comes and we're not a part of it, then we'll become a second-class economic power because we will not be able to participate in the current technology at that moment of cost-effective energy for all purposes. Thank you, Doctor.

I yield back, Mr. Chairman.

Chairman WEBER. I thank the gentleman.

The gentleman from New York, Mr. Tonko, is recognized for five minutes.

Mr. TONKO. Thank you, Mr. Chairman, and thank you to our witnesses for joining us on a very interesting and very important topic.

As the only member representing the State of New York on the Science Committee, I want to address a disturbing budget cut that was brought to my attention. The OMEGA Laser Facility at the University of Rochester's Laboratory for Laser Energetics has been targeted for severe cuts and a three-year ramp-down in the fiscal year 2019 budget request. I along with many of my colleagues strongly believe that OMEGA deserves continued support and that eliminating the facility would be detrimental to national security and the continuity of our nuclear program.

OMEGA provides scientific and technical support for the 400 users from the 55 universities and over 35 centers and national laboratories that use OMEGA annually to conduct more than 2,100 experiments in cutting-edge research. Currently, demand for these facilities exceeds available time by a factor of two. LLE's benefits go well beyond the more than 2,100 experiments OMEGA conducts annually in support of the ICF program. LLE employs more than 360 scientists, engineers, and technicians and support staff. LLE draws 400 scientists from around the world to western New York every year to carry out fundamental research, training, and education. LLE provides a strong stimulus to New York's economy as a source of new startup companies and a driver of the region's optics, imaging, and photonics sector. The LLE's OMEGA Laser Facility is a vital contributor to national security and an invaluable source of scientific education and leadership.

The LLE is the most cost-effective facility in the science-based Stockpile Stewardship Program, performing 80 percent of all the targets shot—used in the national inertial confinement fusion, or the ICF, and high-energy density physics programs with only 13 percent of NNSA's ICF budget. LLE is internationally recognized for its groundbreaking research in high-energy density physics and high-powered lasers. The OMEGA Laser Facility indeed is the major DOE facility that trains graduate students serving as a critical pipeline for future talent that is critically important to our national and economic security.

So I would ask any or all of our witnesses, have you heard any explanation for the cuts to the OMEGA Laser Facility at the University of Rochester's Laboratory for Laser Energetics? Anyone?

Dr. HERRMANN. The Department of Energy, the NNSA budget justification outlined that the resources were shifted to higher-priority activities, but we haven't gotten any more details than that in our conversations with the Department.

Mr. TONKO. So again, to each of our panelists if you choose, what impact with these cuts have on the field, on our national security, and certainly on the workforce?

Dr. HERRMANN. Well, at Lawrence Livermore we work very closely with the University of Rochester and the Laboratory for Laser Energetics. OMEGA serves as an important staging ground for performing experiments before they come to NIF to get the data we need for the stewardship program. We work closely with scientists and engineers at the University of Rochester to develop diagnostics for the National Ignition Facility and to move the science forward, and they really play an important role in the entire national community, so I think would be a very big loss if the OMEGA Laser Facility were shut down.

They're also an important training ground for students who go into this field and can train many future stockpile stewards. Our laboratory has hired many of the scientists who studied or did experiments at the University of Rochester, so I think it would be a big loss to the national program.

Mr. TONKO. And I would think that human infrastructure component is a very critical one.

Anyone else from the panel that wants to address the cuts?

So, Dr. Herrmann and Dr. Wade, there have been some notable efforts made to our progress from those working on innovative fusion energy concepts, and recently the Tri Alpha was featured in a cover story of TIME Magazine for achieving a major milestone while other smaller companies are making progress in addressing other critical technical challenges. If these innovative companies and approaches cannot find funding here in the United States, just where will they go do you imagine?

Dr. WADE. Well, I—to answer your—to give you some background, these companies like Tri Alpha have made tremendous progress in looking at the areas that they're looking at, but as Mr. Weber, the Chairman, said at the beginning of this, the goal is to get high density, high temperature for long periods of times, and these confinement concepts are well behind in terms of the tokamak, in terms of their maturity. They're making tremendous progress, and they may someday be able to get to tokamak levels of performance.

The—in terms of investment by other countries, I would anticipate that China would be involved. China has almost like an Apollo program in almost every energy sector, and so they're launching initiatives in a wide range of areas.

Worldwide, if you looked at the rest of the world, the fusion effort is primarily focused on the tokamak and bringing that into full maturity, bringing other lines that are at second level, second-tier along at a slower pace, so I don't anticipate a large investment worldwide. Probably in China there'll be some effort, and there may be sovereign countries—sovereign funds that invest in small startups to give them seed money to see if they can actually get to the point of making one of these concepts a reality.

Mr. TONKO. Thank you. And, Mr. Chair, I yield back.

Chairman WEBER. The gentleman yields back.

The gentleman from Florida is recognized.

Mr. DUNN. Thank you very much, Mr. Chairman.

This is an exciting and interesting topic. Let's jump in. Dr. Wade, you stress U.S. leadership in fusion research is threatened by large investments by other nations. What level of investment is required for us to compete here? I'm looking for a number.

Dr. WADE. Well, that's a very good question. I think that the level of investment we're making right now is not sufficient. I think that especially when you look at the domestic program and the level of funding that it's at, it's barely at a stage where we can sustain our leadership, much less exert leadership. If I were recommending a number, I would recommend a factor to two or three increase in fusion funding in the United States from the point of view that there are multiple initiatives that we are unable to fund that I think would have benefit not just in providing us an alternative to this mainline approach but to get more people involved in the fusion endeavor——

Mr. DUNN. Sure.

Dr. WADE. —which I think is very important.

Mr. DUNN. And you mentioned the in-kind donations, which I think are terrific because we keep some talent here and grow our knowledge base.

So you've been involved in both the DIII–D project and the ITER project. What's the major difference between those two?

Dr. WADE. The major difference is—well, ITER is about four times the size of DIII–D, so it's a much larger facility. DIII–D is a much more flexible facility in the type of research it can carry out. It's small. It has many capabilities that allow it to—the researchers to manipulate the plasma in a way that——

Mr. DUNN. But the physics are kind of all the same?

Dr. WADE. The physics is exactly the same; it's just at larger scale.

Mr. DUNN. Okay. Can you share some of the spinoff applications that have come out of this program?

Dr. WADE. There have been a huge number of spinoffs in a variety of areas: microwaves, MRIs. One of the best ones I like to use is if you're familiar with the recent deployment of the EMALS system, Electromagnetic Advanced Launch System, on the Gerald Ford aircraft carrier. This has replaced——

Mr. DUNN. Oh, yes.

Dr. WADE. —all the catapults with electromagnetic systems so that they can reduce the footprint of the steam required to do the steam catapults, and this has allowed the—and also much more controlled takeoff, less stress on the plane, less stress on the pilots, and so these are spinoffs that not only have—we're doing this in the—in basic technologies but in very applied defense technologies also.

Mr. DUNN. Do you interact with the MagLab in Tallahassee, FSU?

Dr. WADE. We have interacted with them not—we do not have a strong collaboration, but we have had discussions with them.

Mr. DUNN. So one thing you said earlier impressed me. You seem very, very confident that the ITER facility is going to be able to achieve the sustained fusion and actually even it sounded like you were saying—and it will be commercially viable. Can you share your optimism with us?

Dr. WADE. Yes, I believe ITER is—I have very high confidence ITER will succeed. I have worked in this field a long time, and I have watched the progression of our understanding, and I believe our understanding is sufficient to have high confidence if technically ITER—with its systems can deliver the technical capability, the physics will be there to deliver the power that is projected. And I think that that launches us into a new era in fusion development. I think that countries, nations, people worldwide will recognize that this is a real energy source for the future and we can launch aggressively into that. And if the United States isn't there at the table ready to do something, we're going to be left behind by other nations in delivering that technology for the world.

Mr. DUNN. Thank you very much. So, Dr. Bigot, so it certainly sounds like he has a lot of faith in you. Do you share his optimism?

Dr. BIGOT. Yes, I share. As I say to you, we have the background of several decades of works on smaller devices and smaller facilities, which demonstrate that the physics is robust, okay, the modeling is robust, and my expectation is if we are able to assemble this larger-scale facility, we will deliver.

Mr. DUNN. Well, Godspeed to all of you. Thank you very much for being here.

Mr. Chairman, I yield back.

Chairman WEBER. The gentleman from Illinois is recognized for five minutes.

Mr. FOSTER. Thank you, Mr. Chairman. And I guess I'd like to start out by seconding Representative Tonko's, I guess, unhappiness with the zeroing out of LLE. You know, I think this will be tremendously damaging, including to NIF. I mean, you're absolutely right. I mean, it sort of serves as something analogous to what a test meme used to serve for for high-energy physics where I worked for decades that you actually need when you have a bright idea for a new experiment, you need a low-cost way of testing it out.

In addition, when you look at the way forward, one of the most promising ways to actually get, you know, to ignition is to switch over to direct drive and—which means you then have to then compress in all directions simultaneously, which is something that can be done today, albeit at a lower energy at Rochester. And so, you know, the wisdom of cutting this is really something I don't appreciate.

The other thing is, you know, we're seeing it more and more, this statement that, well, there just isn't enough money. And so I'd like to try to put that in context. Since the economic recovery started, house—the net worth of Americans has gone up by $45 trillion. Well, what we're debating here largely, the investment—the U.S. investment in ITER will maybe be $4.5 billion, okay? And so we're talking about spending, you know, 1/10,000 of the increase in, you know, the U.S. wealth that's happened on something that can provide energy in principle for millennia.

And so, you know, there's I think a pretty strong case to be made that, you know, especially now that the economy has recovered, we are actually—this is going to be money well spent. And I—but I—and I do appreciate the bipartisan enthusiasm we've seen from—almost bipartisan enthusiasm for fusion generally, though I would also like to point out that for those of my colleagues that don't appreciate the difference between fission and fusion, then I'd be interested in knowing whether they're volunteering their district to be the storage location for all of the fission end-products at the end of the energy production.

All right. Now, a few specific questions. You know, one of the things that I've always found useful to look at in understanding whether a project is on track is you look at the contingency reserve, which you highlighted in your previous testimony, that you've established, you know, a project reserve, which I guess in the United States we talk—is contingency. And so I always used to track the amount of contingency remaining versus the fraction of project completed and to see if this extrapolates above or below zero to see if your project's heading for trouble. And is that something that you have over the last, I guess, three years been tracking and what's—what would that graph look like?

Dr. BIGOT. Thank you for this important question. There is contingency, for example, in the U.S. program. For providing the in-kind U.S. contribution, the United States, according to their regulation, has decided to put some contingencies, so contingencies are in-kind for the production. Some of the countries behave differently, but this is on the responsibility of the ITER members.

Within the ITER Organization, when I came in, I was requested to provide the best technically achievable schedule at the lowest cost without contingency. Since that time, we have developed risk management, and I request all my colleagues on the amount of money—that we call the "overall project costs" for the ITER Organization—to make an eight percent saving every year, in such a way that I am building up some contingencies in order to phase in the risk.

Mr. FOSTER. Now, is this contingency fungible across national boundaries?

Dr. BIGOT. Yes.

Mr. FOSTER. Like if country X gets in trouble on their project, can the contingency from savings from country Y be used to bail them out or is there——

Dr. BIGOT. No.

Mr. FOSTER. —a firewall?

Dr. BIGOT. No, there is a firewall—

Mr. FOSTER. Oh.

Dr. BIGOT. —exactly. For the in-kind contribution, there is a firewall. Each ITER member is responsible to deliver the in-kind contribution. But for the ITER Organization, the cost of the assembly, for example, the commissioning and all these things it is according to the share the United States is nine percent, Europe 45 percent, all the non-European countries is also 9 percent.

And I would want to point out something very clearly. For the United States participating in the ITER project costs nine percent of the value of the project, but they will have access to 100 percent of this facility, so I guess it's clearly a good investment.

Mr. FOSTER. And sort of the benefit of scientific collaboration, since science began, that if you collaborate, you learn more. So let's see.

Dr. Van Dam, you mentioned that there was an ongoing administrative—the Administration was going to review the nuclear program generally and science specifically, and you were involved in, you know, the budget pass-back and all of the things which came to the conclusion, for example, that you had to shut down LLE and preserve DIII–D and all these sort of Sophie's Choice decisions that you have to make during the budget decisions. And could you describe—you know, obviously, you can never discuss those in public. That's—for reasons we understand, but could you describe the list of scientists above you in the org chart that are going to be involved in those sort of decisions?

Dr. VAN DAM. Well, yes. Directly above me is the Deputy Director for Science Dr. Steve Binkley. You probably know him.

Mr. FOSTER. Sure, I know him well. Yes.

Dr. VAN DAM. And above him should be the Director of the Office of Science, which at the moment is still vacant.

Mr. FOSTER. All right. And if you continue up——

Dr. VAN DAM. Yes.

Mr. FOSTER. —the org chart, where do you encounter Ph.D. scientists above that in the org chart making these decisions?

Dr. VAN DAM. Well, Dr. Binkley is certainly a Ph.D. scientist.

Mr. FOSTER. Right.

Dr. VAN DAM. Then, above him would be Mr. Paul Dabbar, who is the Under Secretary for Science, then the Deputy Secretary and the Secretary himself.

Mr. FOSTER. All right. So you've just given us the complete list of, say, Ph.D. scientists who are going to be involved in making these crucial decisions about which facilities can survive in different budget scenarios, for example?

Dr. VAN DAM. Well, Dr. Binkley has a Ph.D.

Mr. FOSTER. I understand. He's also a permanent employee of——

Dr. VAN DAM. Yes—

Mr. FOSTER. —not a——

Dr. VAN DAM. —not a political—

Mr. FOSTER. Yes, because I'm personally very nervous that we're making these really important decisions with, you know, frankly no one home, you know, with a—with science credentials in making these decisions, and there are real risks to the program if that proceeds.

Anyway, I think I've gone past my time.

Dr. VAN DAM. May I briefly defend Paul Dabbar, Under Secretary of Energy, who worked in technology for——

Chairman WEBER. Briefly.

Dr. VAN DAM. I'll finish.

Chairman WEBER. I thank the gentleman.

The gentleman from Florida is recognized for five minutes.

Mr. WEBSTER. Thank you, Mr. Chairman.

Dr. Van Dam, when I was in college 40-some years ago in electrical engineering, they said that we're about 30 years away from actually producing electricity through fusion. And now I hear that we're still 30 years away. I'm wondering, has there been any—let's say in the last, I don't know, 10 or 15 years, has there been any progress or notable progress towards the goal?

Dr. VAN DAM. Well, I was also a student 40 years ago and I heard the same thing. I think people did not realize how challenging this endeavor is. It is a very complex endeavor. It's often called a grand challenge problem. I think we have made tremendous progress, and the National Academies study in fact will be documenting that when they do their final report at the end of the year. We've made great progress in control of plasmas just like with airplanes, in high-resolution diagnostics, high-performance computing, and just the—and also the technology that goes along with it, the heating technology, the magnet technology, and so forth. We have a recent FESAC report on transformative enabling technologies that will enable us even to accelerate faster.

Mr. WEBSTER. So—okay, so it seems like back then, there were these goals that were necessary and things that needed to happen to sustain the reaction. And I'm wondering is there one thing or two things that we need to do over the next, let's say, ten years from now in order to say, okay, we've made real progress? Could you name those?

Dr. VAN DAM. That's a great question, and I'm sure my neighbors would be happy to answer as well. I think we need to stay in the ITER project, and the computing is a very, very big priority for us and for the Administration because it lets us take bigger steps forward with confidence having codes with predictive capability. The experiments I think are extremely valuable. We have these very high-performance experiments, 100-million-degree plasmas, and we're understanding them at a very precise level.

Mr. WEBSTER. What was the temperature?

Dr. VAN DAM. Like 100 million degrees. It's quite impressive. And we have these diagnostics that can actually see exactly what's going on, coupled with the codes that actually can compute both postdictive and predictive and interpret what's going on. And material studies, we need that desperately.

Mr. WEBSTER. Is that where we're putting the money?

Dr. VAN DAM. In the 2019 budget we've proposed this linear diverter facility at Oak Ridge. It's called MPEX, Material Plasma Exposure facility——

Mr. WEBSTER. At our——

Dr. VAN DAM. —Oak Ridge National Laboratory.

Mr. WEBSTER. Yes.

Dr. VAN DAM. That's one thing we're doing.

Mr. WEBSTER. Okay. Thank you very much. I yield back.

Chairman WEBER. All right. And——

Mr. FOSTER. Mr. Chairman——

Chairman WEBER. Yes, sir?

Mr. FOSTER. —would it be all right if I had an additional question?

Chairman WEBER. Well, we have a meeting right following this——

Mr. FOSTER. Okay.

Chairman WEBER. —so I would encourage you to get with maybe Dr. Van Dam over the Fusion Advisory Science Committee, which offers—has Ph.D.'s and offers that advice, but I do need to close it out.

I thank the witnesses for their valuable testimony and the Members for their questions. The record will remain open for two weeks for additional comments and written questions from the Members. This hearing is adjourned.

[Whereupon, at 11:43 a.m., the Subcommittee was adjourned.]

Appendix I

Answers to Post-Hearing Questions

ANSWERS TO POST-HEARING QUESTIONS

Responses by Dr. Mark Herrmann

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
SUBCOMMITTEE ON ENERGY

"The Future of U.S. Fusion Energy Research"

Dr. Mark Herrmann, Director, National Ignition Facility, Lawrence Livermore National Laboratory

Questions submitted by Rep. Randy Hultgren,
Committee on Science, Space, and Technology

1. *What kind of workforce is required to operate a facility like NIF?*

   NIF is the world's largest laser. When it was completed it was sixty times more energetic than the next biggest laser in the world. Even today, nearly 9 years after commissioning, NIF delivers ten times more energy than the next most energetic laser in the world. In addition to its unique capabilities as a laser, NIF is a precision experimental capability for studying high energy density science. To maintain and advance this unique capability for its Stockpile Stewardship mission, NIF requires a world class workforce of scientists, engineers, and technicians that span a wide variety of disciplines and expertise, including lasers, optics, materials, computer controls, ultrafast detectors, cryogenics, high energy density science, inertial confinement fusion, and many other disciplines.

2. *What role does NIF play in recruiting and training scientists?*

   NIF plays a critical role in LLNL's recruiting of scientists, engineers, and future stockpile stewards. NIF is our Lab's most visible scientific and experimental capability, and its world leading nature has been and remains a magnet for scientific and engineering talent. NIF has played a key role in our Lab's recruiting strategy since the 1990's.

   In addition to the major role in recruiting the scientists and engineers who are the next generation of stockpile stewards, NIF plays a key role in training the next generation of stewards. In the absence of further underground nuclear testing, NIF experiments, particularly ignition experiments, provide a means of training our current and future workforce in the skills needed to be successful as stockpile stewards. One of the major workforce training aspects associated with underground nuclear testing was the opportunity to work in large multi-disciplinary teams where the successful contributions from all members was key to the success of the test. NIF experiments, particularly ignition experiments, provide that training opportunity for our current and future workforce. Everyone's contributions matter and little details missed could impact the success (or not) of the test. This experience is so valuable that, in fact, many of the current leaders of the SSP have participated in various aspects of the national ICF program.

3. *What mechanisms and programs do you find most helpful in maintaining a workforce pipeline of talent in laser physics and high energy density science?*

   There are several programs we rely on to maintain our workforce pipeline. Since some of the work on NIF is unclassified, and of broad scientific interest to the academic community, we have extensive collaborations with leading professors in high energy density science. NNSA supports dedicating 8 percent of NIF's time to collaborative experiments with universities. In doing so, we establish relationships with professors and their students, many of whom are later recruited to the NNSA's laboratories. Another critical program is NNSA's Joint Program in High Energy Density Laboratory Plasmas. Approximately 50% of LLNL's hires in high energy density science for the last few years have come from universities that have been supported by this program. Finally, the Omega Laser Facility at the University of Rochester has significant experimental time available for university researchers and their graduate students. This provides a unique training ground for graduate students in high energy density science, both at the University of Rochester and many other universities.